POTENTIAL FOR ENERGY CONSERVATION

in the

METAL FORMING INDUSTRIES

Progress Report
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A_o	-	Original cross section area
A_f	-	Final cross section area
C_p	-	Heat Capacity of material
F	-	Force in drawing
$f(\alpha)$	-	Function of cone angle
h_f	-	Final height
h_o	-	Initial height
k	-	Maximum resistance to shear
L	-	Length
L_o	-	Length initial
m	-	Shear factor for friction
$\bar{m}$	-	Average shear factor for friction
n	-	Material constants
O	-	Origin of Coordinates at Apex of Die
P	-	Pressure
R	-	Radius
R_f	-	Final radius
R_o	-	Original (initial) radius
Γ	-	Radial Distance
Γ_o, Γ_f	-	Radial Distance of Γ_1 & Γ_2 from the origin of the spherical coordinate system
$r\%$	-	Percent reduction in area
T	-	Temperature
T_o, T_f	-	Entrance and Exit Temperature

N O M E N C L A T U R E

(continued)

T_{mp}	-	Melting temperature
ΔT	-	Change in Temperature
UTS	-	Ultimate tensile strength
$\dot{U}_r, \dot{U}_\theta, \dot{U}_\rho$	-	Components of velocity vector in a spherical coordinate system
v	-	Velocity
v_f	-	Final velocity
v_o	-	Original (initial) velocity
$\dot{W}$	-	Power (work per unit time)
$\dot{W}_f$	-	Friction power losses
$\dot{W}_i$	-	Internal power of deformation
$\dot{W}_s$	-	Shear power losses
YS	-	Yield strength
z	-	Length of linear (longitudinal) movement of transverse grid line along a split billet
α	-	Angle, die semi-cone angle
α_1	-	Dead zone cone angle
α_{cr1}	-	Critical semi-cone angle for dead zone formation
α_{cr2}	-	Critical semi-cone angle for shaving
α_{opt}	-	Optimal semi-cone angle
σ	-	Stress
σ_o	-	Yield limit at uniaxial tensile stress, also flow stress
σ_{xo}	-	Back pull stress
σ_{xf}	-	Front pull stress
θ	-	Angular position of point

N O M E N C L A T U R E

(continued)

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σ_o	-	Yield limit at uniaxial tensile stress, also flow stress
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σ_{xf}	-	Front pull stress
θ	-	Angular position of point

N O M E N C L A T U R E

(continued)

Γ	-	Boundary of velocity discontinuity
τ	-	Shear stress, frictional resistance to flow
ϕ	-	True strain
ϕ_{eff}	-	Effective strain

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A B S T R A C T

Reduced energy consumption and improved product attributes are realizable benefits that are achievable through the adoption of optimal metal forming techniques. With the meteoric rise in energy costs, certain segments of the metal forming industries have accelerated their efforts in switching from energy intensive manufacturing techniques, e. g., casting, to metal forming, and, furthermore, from hot forming and machined components to cold forming, notably the automotive industry.

This progress report includes the first year results of a two year study that will identify and document potential energy and cost savings associated with the adoption of low energy consumption techniques. When compared with techniques requiring energy for hot forming, heat treatments, and excess or scrap material, the utilization of alternative metal forming processes offer considerable promise for energy savings.

Descriptions of savings achieved by a combination of analytical methods and imaginative new processes are provided in the form of specific industrial case studies. The elimination of defects through the use of an analytical criteria for the prevention of the central burst is presented. Such available criteria for central burst serve as a justification for the desirability to develop criteria for the prevention of fishskin and other defects.

Other savings which may be possible through the development of new technologies are included in an Appendix entitled: "Recent Developments in Wire Making." One specific new process, Continuous Hydrostatic Extrusion, has been developed at Western Electric and is described in detail.

A C K N O W L E D G M E N T

Ms. K. Benusa and Mr. R. Megasko, students in the Department of Metallurgy and Materials Engineering of Lehigh University, assisted in the preparation of this report.

1.0 PROJECT INTRODUCTION AND

OVERVIEW OF METAL FORMING

1.1 Scope of Work Performed:

The information contained in this interim report "Potential for Energy Conservation in the Metal Forming Industries" is based on the results of the first year effort of a planned two year study sponsored by the Department of Energy, Contract EM-78-S-02-4930.A000. As an interim report, only certain tasks of the full study will be discussed in detail, namely Tasks I, II, and III contained in the Proposal and listed below:

Major Tasks

- I Review of Scientific Literature and Trade Publications and Communications with Professional Societies
- II Documentation of Industrial Applications of Mathematical Solutions to Metal Forming Problems
- III Analytical Evaluation of Selected Metal Forming Processes
- IV Judgmental Estimates by Industry of Energy Savings
- V Estimates of Energy Requirements and Projections of Cost and Energy Savings versus Investment
- VI Development of Adoption Network
- VII Report Preparation and Dissemination of Results

Exhibits 1.1 and 1.2 have been reproduced from the Proposal to provide the reader with some background for integrating the first and second year Tasks.

1.2 Interdisciplinary Treatment:

In order to examine the basic question of how an energy conserving technology such as cold forming is adopted by industry, an interdisciplinary research approach is required.

The decision to adopt or not adopt a new technology requires the management of a firm to understand: (1) the technical feasibility of the process; (2) the organizational and production capability of the firm's personnel to bring the process on stream, and (3) the financial risks and rewards for undertaking the adoption of the new technology. Because of the interdisciplinary nature of the research problem, the reported results are presented in an integrated fashion rather than as separate technical, financial, and organizational concerns. This approach also reflects industry's response to a capital intensive energy conserving technology.

The primary hurdles to overcome for adoption are the availability of capital and the perceived assurance of both a rapid payback and an attractive rate of return on investment necessary to attract capital. Reduction in total energy consumed per unit of output is a secondary benefit to the firm, albeit a primary concern for the Department of Energy and the United States as a whole.

1.3 Metal Forming Industries Defined

The term "metal forming industries" requires some elaboration because an unambiguous classification scheme is not easily definable. An adaptation of the Standard Industrial Classification System is to be developed in Tasks IV and V of the second year effort, but for the purposes of the interim report, a metal forming operation will be defined as an operation subsequent to solidification. Thus, metal forming includes the transformation of a preliminary mill shape into a dimensioned mill product as well as the further transformation of mill products into finished parts.

For the metal forming of steel, Exhibit 1.3a identifies the high tonnage industries that also involve considerable metal working after primary steel making.

Those product categories which have high usage in metal forming are identified by numerical code on Exhibit 1.3a. Exhibit 1.3b further

describes the metal forming processes to which each of the product categories is subjected.

1.4 Metal Forming Processes:

The relative position of metal forming to the primary processes of extraction, casting and powder compaction on the one hand, and the finishing processes on the other hand, is displayed in Exhibit 1.4. With few exceptions, the bulk of the products of the metal fabrication industry are shaped by forming or a combination of forming and other processes like metal cutting or joining. Forming operations are classified as those processes where the desired shape is achieved by imparting plastic deformation to the workpiece in the solid state. Classification by:

1. Product
2. Material
3. Forming temperature
4. Nature of deformation (sheet metal vs. bulk deformation)

can also be helpful. However, the boundaries between categories are not perfectly defined. For example, impact extrusion can be classified as a forging process or as an extrusion. It is needless to say that any specific product can be made from a number of materials, by a variety of processes and at a range of temperatures.

The total energy consumed by metal forming processes constitutes only about 6% of the energy consumption throughout the metals industry from extraction to finished product. Moreover, this amounts to only about 3% of total industrial consumption (see Ref. 2 of Sec. 5). Despite this apparently small relative energy utilization, the impact of the metal forming category on energy consumption in the entire metal industry extends far beyond its identified usage of 6%. The role of metal forming processes in saving energy up and down stream in the primary and finishing stages by reduction of scrap, heat treatment, subsequent machining, floor space, and product quality must also be considered.

1.5 Energy Consumption Comparisons:

It should be noted that the metal forming process itself is a most efficient process from an energy point of view. The energy consumed by the forming operation, especially cold forming, is a small fraction of the total energy consumed by the alternative process of casting or the energy wasted through chips and scrap by the alternative process of metal cutting. (see Sec. 4.6, 5.3 and 5.4). Moreover, it should be pointed out that metal forming in its modern version is still a relative newcomer and, although new applications are continually being identified, it is still used only in a small fraction of the industries for which it can provide potential benefits. The main reason for the slowness in adoption is that metal forming, especially cold forming, is a complex process that requires high technology and sophisticated technical expertise. Current progress is greatly accelerated through scientific analysis; transforming the art of metal forming into a scientific approach. (see Sec. 6.1, 6.2 on the prevention of central burst and on the analysis of flow through conical converging dies.)

Thus, metal forming consumes only a small percent of the energy consumed by the total metal industries because of its low energy intensity and its lack of widespread adoption in industries which can utilize metal forming. Since energy savings in primary and finishing processes can materialize through measures taken in the metal forming processes, further adoption should be promoted.

1.6 Reasons for Energy Saving Potential:

The greatest potential for energy saving that results from shifting to metal forming processes and from perfection within the metal forming technology, is due to:

1. Minimizing material use through lighter weight components, elimination of scrap and prevention of defective products.

2. Eliminating intermediate anneal and other heat treatments.

Metal forming technology is highly complex, employing the latest advances in materials, machine design, instrumentation and automation. It also requires a high degree of expertise based on fundamentals of metal deformation behavior.

Progress in adopting metal forming processes for new products depends greatly on the introduction of new equipment which introduces new modes of forming process, and obtaining better insight into the development of mathematical models, simulation computer programs and numerical methods of analysis. Identification of potential energy conservation from shifting to metal forming processes requires investigation of:

1. Energy consumption areas in the metal forming industry.
2. Areas for potential energy savings and their relative intensity.
3. Measures to be recommended for the realization of the potential savings.

Examination of these questions is, perhaps, best facilitated through the study of typical case histories where metal forming processes that reduce the total energy of metal fabrication, have been successful.

1.7 Where and How to save Energy:

The metal forming process is a low energy intensity process. Whenever metal forming, and especially cold forming is substituted instead of other processing, energy savings are obtained. The trend towards wider use of forming operations including cold forming has increased in recent years, especially in the more developed industrialized countries. This trend is motivated by profit considerations which favor metal forming in order to realize cost savings associated with lower energy utilization. With the higher rise in fuel cost projected for the future, energy savings will play a larger and larger role in cost savings plans.

In Exhibit 1.6 the categories of energy conservation areas are listed. The highest potential for energy savings is expected to be obtained by material savings and the concomittant saving of the energy embedded in the

reduced scrap rates that results from transfer to energy saving metal forming processes, applied to wider classes of products by pursuing the following courses of action:

1. Develop better understanding of the underlying metal forming process, and
2. Introduction of new processes and new generations of equipment.

A typical and classic example that demonstrates the progress that analysis can provide to the adoption of a metal forming process (cold extrusion) and its associated material saving through prevention of defects, is described in a case study of the phenomena of central burst (see Fig. 1.1) and the development of a criterion for its prevention (see Sec. 6.3). In addition, Sec. 4.0 contains a case study of tube extrusion and the fishskin defect. In Section 4.3 it is shown that fishskin defects are responsible for a large material waste in wire and tube drawing and extrusion and in impact extrusion.

A similar defect, the edge cracking in strip rolling, is responsible for substantial generation of waste material. Analytical criteria are not yet available for the prevention of these defects which occur widely throughout the metal industry.

An analytical study of these defects can lead to the development of criteria for their prevention, causing in its wake, similar or larger savings than those already realized, or yet to be realized, by the introduction of the criteria for the prevention of central burst.

It should be pointed out that the development of the criteria for the prevention of Central Burst was made possible after many years of devoted pioneering work in the development of the limit analysis technique (see Ref. 6 & 8 of Sec. 6.0) and the application of this technique to specific metal forming processes, including "flow through conical converging dies" (see Ref. 18 of Sec. 6.0).

The broad study of "flow through conical converging dies" led to specific studies of:

1. Hydrodynamic lubrication.
2. Prevention of failure in bi-metal drawing and extrusion as well as in the production of superconducting wire, and
3. The introduction of hydrostatic extrusion as a new technology, including
4. The development of the new process of hi-draw combining hydrostatic extrusion with wire drawing for the production of very fine wire.

The recent momentum in the introduction of metal forming as a viable alternative is largely due to better analysis of metal forming. The success of metal forming is made possible through better knowledge on which old processes are used more effectively and new processes are introduced.

The new techniques and equipment are described in an incomplete manuscript entitled: "Replacing Brute Force." * The introduction of this generation of new equipment, some already in production, some in the laboratory developmental stage, and some yet on the drawing board or plotting mind, was made possible partially due to better understanding of the metal deformation phenomena. Progress here is partially due to new knowledge but it has also become possible due to parallel progress in other fields of technology including materials, electronics, hydraulic systems, controls and automation. For example, hi-draw, a process which combines hydrostatic extrusion and wire drawing, (Ref. 27 of Appendix A) was patented by Robertson in 1895, it was made into a production tool by Sumitomo Electric by 1975, and still requires refinement. Pressure control systems were required before Robertson's dream came true. Promotion of analytical means are easier to support than the development of new equipment, but both warrant continued investigation.

* Rough drafted, most background information collected, a manuscript will be available in the second phase of the project.

The detailed case studies presented lead to the conclusion that cold metal forming requires the least amount of energy of the available metal manufacturing techniques. It is, therefore, recommended that an effort be made to master the cold forming practice to the highest degree possible, and that attempts be made to introduce it, instead of other operations such as machining, to as broad a degree as possible. The gains in energy savings through elimination of material waste (defective products, scrap and flash) are exemplified in the study of Central Burst (Sec. 6.0) and Fishskin (Sec. 4.0). Savings through development of new processes are exemplified by Continuous extrusion (Sec. 8.0).

In summary, in order to focus attention onto the potentials of energy saving in the metal forming industry, each of the following must be considered:

1. The introduction of new concepts in metal forming equipment and processes. Example: Flashless forging, continuous wire making, etc.
2. The conduct of analytical bases necessary to change the metal forming field from art to science.
3. Special attention should be directed to the processes of cold forming.

It is planned to complete the following tasks during the second year of the project:

1. A case study of Precision Flashless Closed Dies Forging.
2. Complete the manuscript entitled "Replacing Brute Force."
3. Initiate a study for the development of a criteria to prevent "Fishskin" in tube making, and
4. Initiate a technology transfer effort through the organization of a three-day short course on "Energy Conservation in Metal Forming."

If continued, this activity should be extended to attend to the task of helping industry in technology transfer by publications, seminars, short

courses and consultations. It would also be desirable to create a center for extending the analytical study (see the impact of the Central Burst criteria) and for the gathering and evaluation of information on new concepts.

1.8 Recommendations for Future Work

This is an interim first year report of an intended two year study of the potential for energy savings in the metal forming industry. It appears clear that the importance of the metal forming industry and its potential for energy savings lies in:

1. Replacing conventional high energy intensive processes by a lower energy intensive process of metal forming.
2. Eliminating material waste which contain high embedded energy consumed in its primary processing.
3. Introducing modern metal forming processes and equipment.

The study of new concepts in wire making is presented in the specific case study "Conventional Wire Drawing versus Continuous Hydrostatic Extrusion, Fuchs' Method" in Sec. 8.0.

The details of the studies of new processes in general (other than wire making) are contained in the incomplete manuscript entitled "Replacing Brute Force." The document is not completed and it is intended to be pursued to completion in the second year of this project, together with the specific study of Precision Flashless Closed Dies Forging.

The study of Central Burst serves as an example where estimated savings (see Sec. 6.3) of some 4.87×10^{10} BTU annually in the automotive industry in the U. S. A. alone were made possible through the development

of a criterion for the prevention of defects. This criterion was developed by gaining an insight into the cause of the defect. The insight was gained by analytical means. It was shown that by preventing fishskin defect further savings of 1.03×10^6 Kg-cm per part produced in the U.S. automotive industry alone can be effected by the development of similar criteria (Sec. 4). The similar natures of the central burst and that of internal fishskin was verified by Guimier¹ et al. There it was shown that internal fishskin is a manifestation of central burst in a heavy wall tube. (see Fig. 1.1). Note that when the shape of the fishskin in the extrusion of a tube is extended to the center, it forms the shape of the chevron.

It is, therefore, recommended that an analytical study for the prevention of fishskin, in order to obtain material and energy savings, become part of a possible extension of the present project on the potential energy savings in the metal forming industry. Indeed, a major energy conservation effort (through elimination of defective products) can be materialized through the development of criteria for the prevention of defects like:

1. Fishskin in rod and tube drawing and extrusion
2. Edge cracking in rolling
3. Aligating in rod and strip rolling

R E F E R E N C E S

1. Guimier, A., El, Haik, R., Rosen, L., and Sanz, G., "Study of the Formation of Central Burst," Publication of the Inst. de Recherches de la Siderurgie Francaise, Nov. 1975.

EXHIBIT 1.1

Interrelationships Among Major Tasks

EXHIBIT 1.2

TASKS - TIME

	Products	Steel for Converting and Processing			Independent Forgings (Not elsewhere classified)	Industrial Fasteners	Steel Service Centers and Distributors	Construction Including Maintenance
		Total Shipments	Less Shipments to Reporting Companies	Net Shipments				
	Ingots, blooms, billets, slabs, sheet bars and tube rounds	358,815	225,191	133,624	473,573	1,595	72,851	71,291
	Skelp	102,454	70,981	31,473			52,763	281,683
2	Wire rods	1,330,508	610,270	720,238	28	231,964	69,702	19,119
1	Structural shapes (heavy)	1,048	99	949				
7	Steel piling	2,058		2,058			907,765	2,158,508
3	Plates	72,180	30,235	41,945	3,208	8,629	1,488,524	1,137,718
1	Rails	31	31				15,623	27,138
7	Railroad Accessories	458		458			9,593	5,598
7	Wheels (rolled and forged)	3	3				1,611	3,713
	Axles							2,078
2	Bars—Hot rolled (including light shapes)	1,167,071	922,291	244,780	517,519	326,660	1,031,950	329,107
	—Reinforcing	26,988	25,893	1,095			203,652	1,692,184
2	—Cold finished	4,042	965	3,077	2,158	40,356	416,251	7,469
	Tool steel	1,770	1,718	52	1,672	8	18,393	612
8	Pipe and tubing—Standard	144,647	85,505	59,142		115	1,108,302	124,484
	—Oil country goods	88,851	72,404	16,447			104,108	6,488
	—Line	37,375	6,176	32,199			299,641	83,944
	—Mechanical	30,466	18,114	12,352			239,176	3,784
	—Pressure	3,234	3,039	195			52,654	3,229
	—Structural	892	423	469			147,856	23,666
	—Stainless	3,820	2,488	1,332			15,872	440
7	Wire—Drawn	427,036	22,370	404,666		162,951	196,071	210,220
	—Nails and staples	4,670	1,055	3,615			231,729	37,596
	—Other merchant wire products	7,610	19	7,591			159,885	45,319
5	Black plate	47,500	3,674	43,826			88,331	21,079
6	Tin plate	15,929		15,929			251,142	711
	Tin free steel	255		255			0,461	105
	Tin Mill products—All other	123		123			16,026	12
4	Sheets—Hot rolled	2,384,024	1,130,973	1,253,051		47,151	3,258,331	624,409
	—Cold rolled	585,891	64,006	521,885		6,246	3,171,399	77,930
(4)	Sheets and strip—Galvanized	49,467	9,083	40,384		1,803	1,342,251	434,310
	—All other metallic coated	14,252	1,931	12,321		4	114,624	71,509
	—Electrical	175	141	34			64,020	
4	Strip—Hot rolled	142,130	115,265	26,865	36	17,435	84,469	45,126
	—Cold rolled	48,759	1,865	46,894		2,690	102,008	2,368
	TOTAL—ALL GRADES	7,104,532	3,425,208	3,679,324	998,194	847,507	15,346,024	7,552,747
	%			4.0	1.1	0.9	16.8	8.3

Similar data not available prior to 1940.

TABLE 16--SHIPMENTS OF STEEL PRODUCTS BY MARKET CLASSIFICATION--1977
ALL GRADES (INCLUDING CARBON, ALLOY AND STAINLESS)

(Net tons)

35
SHIPMEN
All Grad

Contractors' Products	Automotive	Rail Transportation	Ship-building and Marine Equipment	Aircraft and Aerospace	Oil and Gas Industry	Mining, Quarrying and Lumbering	Agricultural	Machinery, Industrial Equipment and Tools	Electrical Equipment	Appliances, Utensils, and Cutlery	Other Domestic and Commercial Equipment	Containers, Packaging and Shipping Materials	Ordnance and Other Military	Export (Reporting Companies Only)	Non-classified Shipments	Total
2,449	348,902	4,017	50	10,098	51,930	916	24,540	257,466	362	23	263	28,609	48,826	85,860	531,180	2,157,425
134,148	70,252	88	489	...	...	143	15,329	378,233	545	1,211	89,162	849	...	48,332	23,956	1,803,837
45,907	54,746	248,270	99,425	174	36,948	15,181	83,632	213,578	9,370	91	2,928	1,240	1,465	66,514	138,939	4,034,624
729,790	209,760	649,766	665,851	9,163	163,113	112,541	140,428	1,656,941	225,695	5,766	30,872	5,975	34,988	71,019	137,552	7,529,244
...	...	1,036,549	955	...	...	11,227	...	3,539	...	...	...	...	...	51,289	...	1,146,320
...	...	357,547	173	...	...	1,567	...	38	...	...	...	...	2	5,249	3,803	384,028
...	...	174,811	55	...	...	1,582	...	5,313	...	...	...	...	23	1,447	...	188,555
...	...	138,701	...	...	...	502	...	278	...	...	...	...	...	2,822	...	144,381
117,994	2,723,730	254,859	26,761	11,900	135,073	268,965	270,856	971,074	106,509	20,390	63,898	1,791	29,990	60,544	1,847,147	9,362,397
42,989	...	...	...	...	97	13,975	66	75	1,293	376	1,147	...	...	19,745	2,202,586	4,179,280
21,908	243,044	4,012	4,258	7,042	6,172	5,221	60,401	353,310	24,361	22,742	27,215	82	10,984	5,521	528,000	1,793,584
...	...	...	...	45	7	85	...	4,743	9	50	...	3	16	60	59,709	55,364
105,037	2,514	2,786	1,524	...	156,204	4,538	9,824	25,757	152,281	1,278	23,060	115	...	44,251	32,154	1,853,316
2,938	...	436	...	...	2,191,164	6	...	...	...	...	175	...	...	84,351	2,707	2,405,446
30,377	253,911	2,333	82	1,652	778,665	1,235	1,700	763	2,962	5	1,051	...	...	29,072	94,726	1,329,885
1,876	256	103	227	...	49,669	2,793	23,824	372,433	4,910	7,609	10,693	141	3,241	12,124	324,596	1,361,692
8,417	503	164	...	...	4,374	2,255	32	70,727	376	23	988	7,166	49	10,104	63,195	217,850
311	37	2	300	47	58,906	13	18,876	1,451	1,732	...	490	...	...	1,466	25,967	290,036
...	...	...	...	...	932	73	20	4,054	1,123	79	456	53	88	645	6,391	32,260
195,450	111,386	2,682	94	233	342	6,869	10,973	112,694	14,462	27,644	245,610	34,468	3,240	9,637	145,266	1,893,958
241	96	237	48	...	62	69	425	1,655	62	...	186	2,388	...	38	...	278,447
504	348	706	...	...	8	221	4,188	2,740	13	...	279	5,264	7	...	1,104	228,177
47,863	10,979	...	...	...	...	...	...	1,991	18,461	19,502	50,697	328,029	32	4,900	...	635,690
617	90,577	...	46	...	...	...	289	6,562	12,198	18,111	33,882	4,038,512	34	231,427	...	4,700,027
222	2,366	40	...	...	...	...	...	2,207	57	20	186	951,551	...	7,803	...	974,273
1,646	44,736	...	...	...	...	...	...	997	151	3,634	3,006	1,036	125	833	...	72,325
703,988	6,297,172	287,659	60,877	2,855	7,084	25,548	415,760	538,273	245,409	172,333	203,258	329,508	17,721	67,413	309	14,568,199
733,250	5,548,720	9,689	768	3,198	3,817	2,369	80,337	303,374	1,162,696	1,436,038	829,134	731,647	26,123	99,897	4,976	17,683,493
43,958	1,394,210	31,463	2,538	93	636	2,373	441,624	46,581	107,094	264,855	128,272	44,793	1,454	16,846	...	5,657,437
68,796	519,522	376	1,949	2,426	261	...	7,823	13,822	15,615	39,894	15,961	3,205	78	36,154	...	922,580
36	6,634	2,985	30	...	1,295	542	293	8,243	481,900	6,104	1,395	...	...	23,606	279	697,296
24,049	485,408	21,927	972	4,539	2,642	4,720	76,964	147,433	31,092	14,858	23,781	58,057	1,911	9,242	...	1,081,516
23,898	170,053	2,295	172	719	753	138	10,109	59,815	28,956	66,515	51,744	139,809	12,598	23,566	440,851	1,185,939
4,499,709	21,490,171	3,237,702	869,342	63,211	3,650,072	486,297	1,648,403	5,566,145	2,638,662	2,129,091	1,845,624	6,714,471	193,435	1,075,654	6,615,482	91,147,267
4.9	23.6	3.6	1.0	0.1	4.0	0.6	1.8	6.1	2.9	2.3	2.0	7.4	0.2	1.2	7.3	100.0

EXHIBIT 1.3a

Courtesy of American Iron and Steel Institute,

AISI Annual Statistical Report, AISI, Washington, D.C., 1977.

EXHIBIT 1.3b

MILL PRODUCTS AND THE METAL FORMING PROCESSES TO WHICH THEY ARE SUBJECTED

- 1) Heavy Structural and Rails
End Product, may be bent occasionally
- 2) Bar & Rod
Forging, Extrusion, Rolling, Rod & Profile Drawing,
Tube Piercing and Extrusion, Rotary Forming, Bending
- 3) Plate Mill
Bending, tube rolling or UOE pressing
- 4) Sheet, Strip
Deep Drawing, Ironing, Rotary forming
- 5) Black Plate
Stamping, Drawing
- 6) Tin Plate
Deep Drawing, Ironing
- 7) Little Further Work
- 8) Seamless Pipe, Tube
Extrusion, Rolling, Drawing, Bending, Rotary Forming
- Welded Pipe
Extrusion, Rolling, Drawing, Bending, Rotary Forming

EXHIBIT 1.4 THE RELATIVE POSITION OF METAL FORMING

EXHIBIT 1.5

CATEGORIES FOR POTENTIAL ENERGY SAVINGS THROUGH THE METAL FORMING INDUSTRY

(From High Immediate Potential, Low Investment to Longer Range,
Large Investment Categories)

- 1) MATERIAL SAVINGS THROUGH
 - a) Prevention of Defects, i.e., Central Burst, Edge Cracking
 - b) Net Shape Production, i.e., Flashless Precision Closed Die Forging, Cold Forming to Minimize Subsequent Machining
 - c) Improved Components Design, Material and Properties, i.e., Beverage Cans and Bottles, 2 vs. 3 Piece Cans
 - d) Minimization of Friction Losses and Wear
- 2) ELIMINATION OR MINIMIZATION OF HEATING, REHEATING AND INTERMEDIATE ANNEAL LOSSES
 - a) Cold vs. Hot Forming, i.e., Optimal Heating Temperature
 - b) Continuous vs. Intermittent Processing, i.e., Wire Drawing vs. Continuous Extrusion
 - c) Direct Resistance Heating and Induction Heating vs. Oil Furnace Heating

EXHIBIT 1.5 (2)

- 3) ANALYSIS TO OBTAIN BETTER INSIGHT TO METAL FORMING
PROVIDING SIMULATION MODELS, CRITERIA FOR PREVENTION
OF FAILURE AND CHOICE OF PROCESSING PARAMETERS
- 4) NEW CONCEPTS AND INNOVATIONS, e.g., POWDER METALLURGY,
FINE BLANKING, CONTINUOUS EXTRUSION

ROD EXTRUSION

HEAVY WALL TUBE

FIG.I.I COMPARISION OF FISH SKIN TO
CENTRAL BURST.

2.0 SOURCES CONSIDERED FOR CASE STUDIES

2.1 Machine Tool Manufacturers :

In the expectation that manufacturers of metal forming equipment would be influential in leading their customers in advanced metal forming technology, officials of the National Machine Tool Builders Association (NMTBA) and representative member firms were contacted. It was thought that manufacturers of metal forming presses would utilize the cost and energy savings potential available from advanced metal forming techniques as a sales device in promoting their products.

Persons contacted:

Mr. Charles Pollock, Public Relations Director, NMTBA
Mr. Robert Gale, former Director of Statistics, NMTBA
Mr. Edward Loeffler, Technical Director, NMTBA
Mr. Norman Dunlap, Exec. V. P., Minster Machine Co.
Mr. Jack Danly, V. P. of Engineering, Danly Machine Co.
Mr. C. O. Jones, Niagara Machine & Tool Works

Unfortunately, the expected use of advanced metal forming technology as a promotional device by established manufacturers of metal forming equipment does not generally occur. It appears that new generations of machine tools appear to be few and far between and do not lead the technology of metal deformation. Rather, presses are bought on general specifications and not on specific application of extrusion or blanking capabilities. Presses are sold by capacity such as tonnage, bed size, etc. rather than by specific application. Hence, research and adoption potential of energy saving metal deformation techniques must be sought among users of metal forming equipment and the rare aggressive newcomers rather than the established manufacturers of such equipment.

Research has been initiated on new concepts that are gaining acceptability and which are based on new generations of manufacturing equipment. The replacement of brute force through the introduction of new generations of equipment that will utilize more advanced technology is a goal of this research effort. A typical example; the introduction of "precision flashless closed die forging" is intended to be studied in the second year of the grant. The forging material is available, and a manufacturer has been identified. However, the concept is so new that the manufacturer has asked for a delay to establish his proprietary status before making the concepts available to the public. It should be noted here that for this new concept to be established a special non-standard press had to be used. The press manufacturer, Kimetsu of Japan, is utilizing a new design concept and is a newcomer to the press builders community. The company has a backlog of orders of several years and dominates the American market for this specific application.

Another example of a new concept leading to new equipment is provided through the study of continuous wire making at the Engineering Research Center of Western Electric and is described by a case study later in the report.

It should be emphasized that the introduction of new equipment based on advanced concepts should be regarded as a potent energy saving measure and a focus for future DOE effort.

2.2 Powder Metallurgy Applications:

The primary use of powder metal parts is to obtain the material saving that results from being able to produce precision parts from powder in a press. Savings in material, reduced machining, and potential for improved properties also have energy savings implications. In order to evaluate this potential, a number of inquiries were made in the powder metallurgy industry.

Persons contacted:

Mr. Weston H. Feilbach, Jr., Asst. Director of Research,
Hoeganaes Corporation
Mr. Peter K. Johnson, Director of Public Relations,
Metal Powder Industries Federation (MPIF)
Mr. Donald Gustafson, Metallurgist, Gould Industries
Mr. Sydney Kaufman, Manufacturing Development Laboratory,
Ford Motor Company

Although powder metallurgy is a candidate for energy saving in terms of material saving and possibly improved properties, and although case studies were available from MPIF and other literature, it did not appear desirable to pursue this area in great detail because of the small volume of powder metal parts produced. Iron powder parts, the largest in terms of usage, amounted to only 160,000 tons in 1977, and, although growing, it increased at a rate of only 2.5% in that year. Moreover, approximately 75% of the ferrous powder parts end up in the auto industry, an industry which was examined carefully in the study and one which is very sophisticated in its technological applications, suggesting that most powder metallurgical applications were already adopted or under study. Significantly also, powder metallurgy applications do not lend themselves to the same kind of analytical treatment that underlies cold or warm deformation processes. Thus, because of low volume, high levels of prior investigation, and differences in preparatory analytical study, powder metal applications were not given further consideration as a case study source.

2.3 Alcoa:

Alcoa is the world's leading producer of aluminum. In addition to the production of primary aluminum by the company, Alcoa ships nearly two million tons of fabricated aluminum products. Because of the very high quantities of energy consumed in the production of primary metal, Alcoa is quite concerned about energy research and is currently conduct-

ing several sponsored research projects for DOE. With respect to the downstream working of aluminum after solidification and primary shape formation, Alcoa has a keen interest in energy conserving technologies for their rolling and forging operations.

A visit was arranged between the Lehigh University researchers and the following individuals from Alcoa:

- Mr. James D. Dowd, Asst. Director, Fabricating
- Mr. C. Norman Cochran, Manager, Physical Chemistry
- Mr. Allen C. Sheldon, Vice-President - Environmental and Energy Resources
- Dr. G. Keith Turnbull, Manager - Fabricating

The problems of edge cracking, recovery (decrease in scrap), and technical assistance for customer applications were research areas that were considered to be of importance to Alcoa and related to the scope of the DOE Project. When it was proposed that these areas be pursued strictly on a technical corroboration basis, i.e., Alcoa would provide empirical data that would be compared with analytical results from Lehigh University, Alcoa expressed a strong concern over the confidentiality of the information and chose not to participate in the Project.

2.4 Bethlehem Steel Company:

The steel industry is the largest user of energy in the country. In general, integrated steel firms have tended to concentrate their efforts on energy conservation in steel making processes because of the large amounts of energy consumed in that segment of their operations and the correspondingly large potential for conservation. As a result, relatively little has been done regarding the energy conservation potential in the fabricating shops of steel firms. Despite this background, it was deemed prudent to visit the research laboratories of the Bethlehem Steel Corporation to assess their willingness to participate with us in the development of an appropriate case study in the area of central burst or another application.

Persons contacted:

Mr. John Werner, Assistant Div. Mgr., Primary Processes Research
Mr. Peter Kromeyer, Corporate Engineering Department
Mr. Harry Sutherland, Supervisor, Research Energy Studies

At the outset of the discussion it was clearly pointed out that many energy saving technologies in the steel industry are known and the problem in implementation is not energy conservation but rather the size of the cost savings relative to the capital requirements, i.e., unacceptable rates of return or too high hurdle rates. Setting aside the energy saving potential prior to ingot formation at which point approximately 65% of the energy content of finished steel is expended, an attempt was made to focus on the energy conservation potential in the finishing and semi-finishing processes.

Energy efficiency improvement in hot rolling is possible through improved scheduling and reduced overall energy consumption. The overall goal here is to take delays where they are least costly in terms of energy. Examples of costly delays might be in allowing hot work to cool or furnaces to idle while waiting for work. In order to make the total process more efficient, greater sophistication in all kinds of controls and computer scheduling would be required. A major cause of existing energy inefficiency lies in the fact that many existing facilities were designed when energy supplies were freely available and cheap. Hence losses were not taken as seriously as is now necessary under present energy cost and availability.

It appeared that there may be considerable potential to improve the efficiency of hot rolling at lower temperatures than now used. As in most techno-economic processes, there is a trade-off; in this instance, between furnace energy to heat the work and the mechanical energy needed to roll the product. In such an evaluation careful consideration must be paid to the capital considerations implicit in any change in rolling procedures. This situation seemed to have potential for a case study and one with rather widespread application. Our request to participate with

Bethlehem Steel in developing such a case study was denied for a number of reasons ranging from excessive over-commitment of existing personnel to disappointment with past technical interaction with the Department of Energy.

It was further acknowledged that several energy conservation cases exist which are proprietary and cannot be revealed because of the interests of vendors. Based on the discussion, it appears that the industry is well aware of the advantages of cold forming, however, full implementation may have to be deferred until capital and cost justification are sufficiently attractive.

2.5 Chrysler Corporation:

The Precision Forming Laboratory was formed at Chrysler in 1972. At that time its principal objective was to implement cost saving processes in manufacturing. However, material savings became an important goal during the material shortages of 1973 and 1974; and since then there has been considerable emphasis on energy savings. The group has grown and prospered since its inception. It has relied extensively on the application of mathematical analysis to metal deformation processes and, in its growth from two to sixteen employees, a mathematician has joined the staff.

Persons contacted:

Mr. Michael E. Ward, Supervisor, Precision Forming Laboratory
Mr. Dale A. Stankiewicz, Sr. Development Engineer, PFL
Mr. David A. Gatny, Development Engineer, PFL
Mr. Arnold G. McDonald, Manager, Metallurgical Processes
Mr. Joseph J. Knapp, Plant Engineering Department

The Detroit Forge plant of Chrysler Corporation is the single largest user of energy in the corporation. Energy saving areas in the precision forming area include reductions in process temperature, heater improvement and forming improvements. The evaluation of modifications to each of these procedures is highly analytical. Forge temperatures

may vary 300° - 400°F for making of the same part. The group is seeking to minimize process temperatures consistent with deformation energy requirements. Collateral benefits here include improved tool life.

The energy conservation projects that have most promise are those that have minimal capital requirements. Projects that require large amounts of new capital tend to have poor payback periods, e.g., five years or more, and are difficult to obtain funds for when money is tight. Overall, it appears that the analytical work has been effective in reducing trial and error approaches. Although implementation has been a difficult problem, considerable improvement is anticipated due to the added emphasis on energy and cost savings.

After certain reservations, Chrysler indicated a willingness to participate in the development of a case study. The part selected for the study was a rear axle drive pinion. This part was formerly a multiple hit forging. It is now made by cold forward extrusion and warm upsetting. In supplying analytical and energy data on this case study, Chrysler indicated that although much energy was saved, it was not nearly the maximum savings possible. Many trade-offs have had to be made, and, in their evaluation, cost savings were the criteria for the adoption of any measure, while energy savings followed automatically as a by-product.

The rear axle drive pinion was a member of a family of parts which should lend themselves to a similar analytical approach. Moreover, there appear to be numerous other families of parts that are amenable to precision forming techniques, many of which reflect substantial energy conservation potential. In the second year of the study an attempt will be made to provide a framework whereby an estimate can be made of the magnitude of energy saving that might be possible from shifting to more energy efficient metal forming processes.

2.6 Ford Motor Company:

The Manufacturing Development Laboratory at Ford Motor Company has a very active group dealing with metal forming technology and processes.

This organization has existed for many years and has developed considerable expertise in all aspects of metal forming applications. It was thought that because of their extensive background this organization would be able to participate in the development of a case study for the project.

Persons contacted:

Mr. G. S. Hauser, Supervisor, Metal Forming & Joining Department

Mr. Benjamin I. Bachrach, Metal Forming & Joining Department

Mr. Sydney Kaufman, Metal Forming & Joining Department

Mr. Harry Johnson, Metal Forming & Joining Department

Mr. Stanley Mocarski, Metal Forming & Joining Department

Because of the emphasis on reclaiming waste materials, use of recycled materials, energy conservation and congressional mandated mileage goals, there has been extensive attention directed to material saving and weight saving substitutions in all components of automobiles. Analytical methods continue to be an important ingredient in the evaluation of transition to material saving or energy saving component fabrication processes. Moreover, good candidates for analysis are those parts for which many other alternatives for fabrication exist. And the best candidates are those which are similar to others in the same family of parts so that what is learned in shifting one part to less energy intensive fabrication processes, can be applied to other parts in the same family of parts.

As a result of our discussion, it was agreed that Ford would participate with us in the development of a case study. The part chosen was the F10D forward sun gear blank which had been fabricated in the past by alternative methods, including machining from bar stock, machining from seamless tubing, and hot forging. The expected volume in 1980 is approximately one million parts per year at Ford. Moreover, another part approximately seven-eighths the size with the same volume is being evaluated. The characteristics of the part are a large head and small

stem with a hole in the center. Three such parts are used in each transmission system on rear wheel drive vehicles. This application and the related analysis and energy conservation potential is presented in the section on case studies that follows.

2.7 GTE-Sylvania:

Because of known analytical work on metal deformation by personnel at the Precision Materials Group of the Chemical and Metallurgical Division of GTE Sylvania in Towanda, Pennsylvania, it was decided to visit the group to evaluate the feasibility of a case study for the project. The application in Towanda is one of drawing fine tungsten wire for lamp filaments. The process begins with compaction of tungsten powder, sintering, a swaging operation to obtain sufficient material strength for subsequent hot drawing of rod and wire.

Persons contacted:

Dr. James Mullendore, Head, Metals Research

Mr. Charlesworth, Chief Engineer, Rod & Wire Works

Mr. James Steigeler

Mr. Stanley Potts, Division Energy Coordinator

Mr. Robert Zalinski, Metal Working Specialist, Rod & Wire Works

Tungsten wire drawing is done hot. Energy saving possibilities centered upon the prospect of further increases in drawing speed through studies of optimum die design, lubricant, reduction, etc. Investigations in this area are underway and suggest that the most significant energy savings will probably lie in the reduction of rejects that can be obtained by fine tuning the manufacturing process.

Considerable concern was expressed by the firm over the loss of competitive advantages that results from improved manufacturing methods if a case study were to be developed for this application. The firm was very proprietary conscious.

This Sylvania plant is a typical powder metallurgy plant with relatively small volume. Their lack of interest, concern over proprietary matters and low volume of specialized tungsten products, led to a conclusion to discard this application as a potential case study.

2.8 Western Electric Company:

The metal working of copper can be epitomized by the Western Electric Company's drawing of rod into billions of conductor feet of copper wire for the telecommunications needs of the Bell System. Although technological advances in copper wire drawing have mostly been evolutionary in nature, Western Electric has been conducting research since the mid 1960's on a revolutionary technique for extruding wire known as Continuous Hydrostatic Extrusion. The inventor of the process, Mr. Frank Fuchs, a research engineer at Western Electric, has had a long association with Lehigh University's Institute for Metal Forming. In addition to the work on Continuous Hydrostatic Extrusion that was done at the Western Electric Research Center in Princeton, New Jersey, experimental effort on the process has also been conducted at Western Electric's Atlanta, Georgia, production facility. Mr. Charles B. Heard, Asst. Manager, Development Engineering, and Mr. Glenn Schmehl, Department Chief, Insulating and Screw Design Engineering, were also interviewed by Lehigh University about the Fuchs Method for extruding copper wire and provided some insights into production hurdles to be overcome.

WE proved to be a very cooperative participating company for the DOE Project, and full details of Continuous Hydrostatic Extrusion are provided in the case described in Sec. 8.0.

2.9 Observations from Case Study Sources:

A number of common ideas surfaced during our discussions with firms who represented potential case studies. In order not to disclose an identification with any single firm, these observations are presented here as reflecting the response of most of the firms interviewed.

A. Interest in analytical studies to improve the efficiency of metal deformation methods have been and still are primarily cost motivated rather than energy motivated. Despite the severe increase in energy cost and decreased availability, cost considerations still prevail and energy conservation that cannot be cost justified remains largely unexploited.

- B. The energy content of metal removing processes is relatively insignificant compared with the energy content of the material that is converted to chips (scrap) and the energy used in heat treating the part.
- C. In many instances, cold forming processes are developed in research and development but remain unaccepted by manufacturing operations. Reasons for this include inertia and suspicion, but more genuinely lie in the existence of large stocks of capital equipment available to produce output in the conventional way, and the high cost of replacement equipment to implement the energy saving procedures. This problem is quite representative of many examples of technologically induced obsolescence that is tolerated because of insufficient returns to justify replacement of existing fixed assets that are perfectly capable of performing for many years into the future. The implications regarding capital formation and availability are broader than the objectives of this study, but they have had an impact on the adoption of energy saving projects.
- D. Energy saving opportunities in fabrication of production parts represent a very small part of the overall energy saving potential in industry. Moreover, the potential in sheet forming procedures is nearly negligible. The major potential lies in those parts formerly made from bar stock by machining or forging. Complex shapes, large reductions and high alloy content present a major challenge to cold forming. The higher deformation forces needed in these instances require new generations of rigid and strong presses of advanced designs. Complex shapes and large reductions in less ductile alloyed steel require better control of steel quality and better understanding of die design for flow without fracture. These difficulties can deter the transition to cold forming, with less competent designers becoming discouraged and concluding that transition to cold forming is not possible.

On the other hand, more aggressive and visionary companies and countries proceed further to achieve the 'impossible'. For example, cold forming as a process, and equipment for cold forming to achieve it,

are much more advanced in Japan, and metal deformation considered unattainable and sometimes claimed to be impossible elsewhere, are becoming present day production practices there. It could be foolhardy for any industry to claim that all that can be done in the transfer to cold forming has already been accomplished.

In discussing this matter with representative industrial personnel, we found that a conservative view is that "perhaps only five percent of parts now hot forged are candidates for cold forming." On the other hand, at a Japanese press manufacturing company called Aida, a subdivision was formed for the study of candidate components for cold forming. They design the necessary tools and process for new cold forming candidates. Twenty presses are at their disposal with a staff that includes a dozen engineers studying new potential for cold formed parts. They do not lack components to be studied and are not held back by shortage of manpower and facilities. The company comes up with new "miracles", constantly expanding the scope of cold forging for their press users. Thus one may say that on the very optimistic side of the estimate, there is potential for increased adoption of cold forming methods over other more energy intensive practices.

E. Induction heating appears to have significant energy conservation potential over slot furnaces. Not only are electric utilities more efficient in controlling losses than industrial heating operations, but induction heating allows for more programmed production, localized heating of the section of a work-piece where heat is desired, reduced scale and shrinkage, lower decarburization and quicker heating of the part. In general, overall energy efficiencies from induction heating compare favorably with conventional furnaces, but because of capital limitations the transition to induction heaters will move slowly as replacement units are required.

F. The potential for energy conservation in metal forming processes within a firm will vary with the past and present degree of technological sophistication of the individual company. Many companies have

already reached plateaus in their conversion from hot to cold worked parts while others are still in a stage of rapid transition with high energy saving potential. In those firms where cold formed procedures are mature, only new product designs lend themselves to cold formed methods. Most available applications have already been taken down for cost reason. The transition from full machining to cold forming is not quite as fully realized as that from hot to cold forming. The potential that remains here should justify the on-going search for more efficient methods that is underway in major firms.

G. The transfer of technology from firms that develop it to others through some sort of an adoption network is limited at the early stages of a new development. However, after a development gets into production and is proven, the risk of wasting development cost is lessened and competitors are willing to try to imitate the success of others. This can be accomplished by simply buying a competitor's product and studying how the parts were fabricated, or by using the same supplier that the competitor used and thus obtaining similar technology. Nevertheless, most astute firms don't stand and wait for others to develop parts and new fabrication methods. They all try to stand in the forefront of new technology, but when one makes a breakthrough, the others evaluate and imitate in a rather short period.

H. Most firms are very concerned about government actions in the area of energy and the many other spheres where regulation has progressed. They are very sensitive to dealing with government and government sponsored projects. It appears that no more than modest technical cooperation will be forthcoming until it becomes apparent that government programs have the balanced interest of the industrial sector as well as the interest of other sectors at their core.

3.0 FUNDAMENTAL ENERGY CALCULATIONS

RELATED TO CASE STUDIES

3.1 Isothermal versus Adiabatic Processing

Analytical solutions to most metal forming processes have, in the past, assumed a perfectly plastic material as the processed medium. This implies a simple Mises material which does not strain harden or show strain rate effects. The processes are also assumed to be isothermal. A more realistic analysis would assume an adiabatic process which incorporates strain hardening and strain rate effects. Such an analysis was conducted by B. Avitzur, for metal flow through conical converging dies, (see Refs. 1, 2, 3 for a complete description). Criteria for calculating the metal forming energy requirements found in this report were obtained from calculations based on that particular analysis. A brief summary of that analysis will be given here.

A spherical velocity field for metal flow through conical converging dies was assumed. This spherical field was then divided into small elements, finite in number. Each element is then treated individually by an upper bound approach (see Ref. 4 for complete details of upper bound analysis methods for conical converging dies) to determine the flow strength, as a function of temperature ($\sigma_0 = \sigma_0(T)$), the effective strain and effective strain rates, ($\sigma_0 = \sigma_0(\phi, \dot{\phi}, T)$). This allows the stress, strain and power consumed to be calculated for each element in an explicit form.

During flow through conical converging dies, the independent process parameters (see Fig. 3.1) are:⁴

- 1) The radius ratio, (R_o/R_f)
- 2) The semicone angle of the die, (α)
- 3) The friction between the die and the rod, (m)

- 4) The material characteristics. (In a symbolic form the materials flow strength characteristics as a function of temperature, effective strain and effective strain rate is given as $\sigma_0 = \sigma_0(T, \phi \text{ and } \dot{\phi})$. The specific heat, C, and other constants are also included as independent material characteristics. (See Ref. 2 for complete details).
- 5) Starting temperature, (T_0)
- 6) Process speed, (v_0 and v_f)

The dependent parameters are:

- 1) The drawing or extrusion force needed, ($\frac{\sigma_{xf}}{\sigma_0}$ or $\frac{\sigma_{xb}}{\sigma_0}$), which is a function of reduction, cone angle and friction, $\sigma_{xf}/\sigma_0 = f_1(R_0/R_f, \alpha, m)$ or $\frac{\sigma_{xb}}{\sigma_0} = f_2(R_0/R_f, \alpha, m)$.
- 2) The temperature rise, (ΔT). The temperature rise occurs because the work done is converted into heat.

The entrance temperature and flow strength for a small element at the entrance of the spherical velocity field is known. The drawing or extrusion force can then be calculated by:⁴

$$\frac{\sigma_{xf}}{\sigma_0} = \frac{\sigma_{xb}}{\sigma_0} + 2f(\alpha) \ln\left(\frac{R_0}{R_f}\right) + \frac{2}{\sqrt{3}} \left[\frac{\alpha}{\sin^2 \alpha} - \cot \alpha + m(\cot \alpha) \ln\left(\frac{R_0}{R_f}\right) + m \frac{L}{R_f} \right] \quad \text{Eq. (3)}$$

$$\text{or } \frac{\sigma_{xb}}{\sigma_0} = \frac{\sigma_{xf}}{\sigma_0} - 2f(\alpha) \ln\left(\frac{R_0}{R_f}\right) - \frac{2}{\sqrt{3}} \left[\frac{\alpha}{\sin^2 \alpha} - \cot \alpha + m(\cot \alpha) \ln\left(\frac{R_0}{R_f}\right) + m \frac{L}{R_f} \right] \quad \text{Eq. (3.2)}$$

where

$$f(\alpha) = \frac{1}{\sin^2 \alpha} \left[1 - (\cos \alpha) \sqrt{1 - \frac{11}{12} \sin^2 \alpha} + \frac{1}{\sqrt{11 \cdot 12}} \cdot \ln \left(\frac{1 + \sqrt{11/12}}{\sqrt{11/12} \cos \alpha + \sqrt{1 - \frac{11}{12} \sin^2 \alpha}} \right) \right] \quad \text{Eq. (3.3)}$$

See Eq. (8.17a, b and 8.11a) of Refs. 4.

For small semicone angles (α), $f(\alpha)$ converges to 1. For the purpose of illustration and for easy understanding one does not need to carry the precise expressions of Eqs. (3.1) ÷ (3.3).

If we assume the shear and friction losses to be zero, the function $f(\alpha)$, Eq. (3), to be 1, and that all the work of plastic deformation is converted into heat, then the power of plastic deformation at the first element or region (see Fig. 3.2) is : $w = 2\sigma_0 \ln \left(\frac{R_0}{R_f} \right)$. Eq. (3.4)

The rise in the temperature of that element can be found by dividing that power by the material's specific heat, i.e.

$$\Delta T = \frac{w \text{ [kg * cm]}}{C_p \text{ [kg * cm/cm}^3\text{/}^\circ\text{C]}} \quad \text{Eq. (3.5)}$$

This temperature change is then added to the initial (or entrance) temperature to find the temperature at the interface between elements 1 and 2. The average temperature of element 1 is then determined and a new flow strength for element 1 is established. The power of deformation, flow strength, average flow strength and temperature rise are reevaluated until they converge to a stable value.

The stable new exit temperature from region 1 becomes the initial (or entrance) temperature of element 2. A flow strength value is calculated using the initial temperature of element 2. This, in turn, through Eqs. (3.4) and (3.5) calculates the power of plastic deformation of element 2 and the interface temperature between elements 2 and 3. The iterative procedure is repeated until stable values are established.

This element by element process continues across the entire spherical velocity field. Schematically, the method is described by the following loop:

$$\begin{array}{lcl}
 \rightarrow P = w = 2\sigma_0 \ln \frac{R_0}{R_f} = \sigma_0 \ln \frac{A_0}{A_f} & & \\
 \downarrow & & \\
 \Delta T = \frac{w \text{ [kg * cm]}}{C \text{ [kg * cm/cm}^3\text{/}^\circ\text{C]}} & & \\
 \downarrow & & \\
 T_f = T_0 + \Delta T & & T_{ave} = T_0 + \Delta T/2 \\
 \downarrow & & \\
 \leftarrow \sigma_0 = \sigma_0 (T) & &
 \end{array}$$

where: P - Extrusion Pressure
w - Work Per Unit Volume
 σ_0 - Flow Strength of the Workpiece
 R_o, R_f - Original and Final Radius of the Workpiece
 A_o, A_f - Original and Final Cross Section of the Workpiece
T - Instantaneous Workpiece Temperature
 T_o - Original Workpiece Temperature
 ΔT - Temperature Rise
 T_f - Exit Temperature
 T_{ave} - Average Temperature
C - Specific Heat

The TOTAL power of plastic deformation is the sum of the powers of plastic deformation calculated by the above method.

Mathematically it is:

$$W_{TOTAL} = \sum_{i=1}^N 2\sigma_0 \ln \left(\frac{R_o}{R_f} \right) \quad \text{Eq. (3.6)}$$

where: N is the number of elements in the spherical velocity field.

The total power of plastic deformation in $[\text{kg}/\text{cm}^2]$ can now be related to the total energy required for the process. The total energy used in the example would be:

$$\text{Total power of plastic deformation} \left[\frac{\text{kg}}{\text{cm}^2} \right] \cdot \left[\frac{\text{cm}}{\text{cm}} \right] = \text{ENERGY} \left[\frac{\text{kg} \cdot \text{cm}}{\text{cm}^3} \right]$$

This analysis was performed, taking into consideration the shear and friction losses as well as the power of plastic deformation, by a computer program developed from Ref. 1. The program is available at the Institute of Metalforming, Lehigh University, Bethlehem, Pa.

In the present work on energy considerations in metal forming the procedure described above for flow through conical converging dies, was also applied to the process of forging. The incremental steps in a forging application consider the progress of the deformations from the initial position of the ram down to the end of the stroke.

3.2 Energy Cost Per Ton of Steel Product:

In order to approximate the energy cost related to the production of one ton of steel product (these products being steel rods, bars, plates and sheets) two sources were utilized. The first source is from an analysis of the Economics of International Steel Trade by Putnam, Hayes and Bartlett Inc. These researchers reported in 1977 that the energy cost per ton of steel product in the U.S. in 1975 was \$62.14⁵. If inflated by a conservative factor of 4% per year, this figure becomes \$69.90 in 1978.

The second source, the Annual Survey of Manufacturers⁶, was used to obtain three average values for the cost of energy per ton of steel. The survey reported the average cost of energy per million BTU in 1976 as the following:

- 1) \$2.19 based on total consumption
- 2) \$2.80 based on coke usage
- 3) \$2.27 based on primary metals industry usage

Applying the value of 29×10^6 BTU's as the energy content of one ton of steel product⁷ (8.047×10^3 kcal/kg, the cost of energy can be calculated. These figures generate a cost of energy per ton of steel as \$63.21, \$81.60, and \$65.83, respectively. The overall average is \$70.08 in energy costs per ton of steel. This value is in fair agreement with that obtained from the first approach. Therefore, the cost of the energy necessary to produce a ton of steel product is taken to be \$70.00/ton of steel in 1978. This value will appear as the base cost of energy per ton of steel throughout the entire report.

It is interesting to note that in May 1979, the average price of steel product was reported to be \$.1927/lb. or \$393.40/ton.⁸ The \$70.00/ton in energy cost comprised approximately 18% of the total value of the product.

3.3 Calculation of Annealing Energy:

The ideal annealing energy can be calculated using the following relation:

$$W_{Ai} = C_p \cdot \Delta T \quad \text{Eq. (3.7)}$$

where: W_{Ai} is the ideal annealing energy in $[\text{kg} \cdot \text{cm} / \text{cm}^3]$,

C_p is the material's heat capacity at constant pressure in $[\text{kg} \cdot \text{cm} / \text{cm}^3 / ^\circ\text{C}]$,

ΔT is the change in temperature in $[^\circ\text{C}]$.

Although the heat capacity is a function of temperature expressed mathematically as:

$$C_p = a + bT + cT^2 + \dots + eT^{-2} \quad \text{Eq. (3.8)}$$

where: $a, b, c, \dots, e$ are constants,

and T is the temperature.

A first order approximation can be obtained by assuming a constant heat capacity over the temperature range in question or

$$C_p = a \quad (\text{from } T \text{ initial to } T \text{ final})$$

This constant heat capacity assumption is employed even though the material proceeds through a phase change, for example, during a normalizing anneal. A constant heat capacity of $40.3 \text{ kg} \cdot \text{cm} / \text{cm}^3 / ^\circ\text{C}$ is used in this report for steel materials. A constant heat capacity of $34.91 \text{ kg} \cdot \text{cm} / \text{cm}^3 / ^\circ\text{C}$ is used for oxygen free, high conductivity copper.

The actual or total annealing energy would equal the ideal annealing energy if the annealing furnace operated at 100% efficiency. Since commercial annealing units are not that efficient, the total annealing energy increases as the furnace efficiency decreases. A common figure for commercial oil burning annealing furnace efficiency is 7%. Therefore, the total annealing energy will be, at least, an order of magnitude higher than the ideal annealing energy.

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$$\sigma_{xf} = f\left(\frac{R_o}{R_f}, \alpha, \text{ AND } m\right)$$

FIG.3.1 THE DIE AND THE WIRE .

FIG. 3.2 FLOW PATTERN AND DIVISION OF THE DEFORMATION REGION.

4.0 COLD EXTRUSION VERSUS HOT FORGING AND MACHINING

OF A FORWARD SUN GEAR

This case study considers the energy conserved as a result of reducing the raw material usage during the production of a Forward Sun Gear F10D by the Ford Motor Company. It was found that a substantial energy savings could be effected by changing the production process, thereby reducing the raw material input. Additional energy savings were obtained with the elimination of the intermediate and final part anneals. These energy savings were realized by the transition of the metal forming process from hot forged and machined to cold formed by tube extrusion.

4.1 An Historical Perspective of Tube Making:

Tube and tubular products have their origins in antiquity. The Egyptians are suggested to have produced gold wire ornaments by pulling hammered, flat sheets through conical converging dies as shown in Fig. 4.1.^[1] Although this process results in a tubular product, if enough reduction is induced, an "almost solid" wire is produced.

Ancient Rome had its tubular products in the form of lead pipes and conduits. These were produced from strips that were bent to form a circular column locked in position by lips which were hammered flat to seal the connection.^[2] (Fig. 4.2). These relatively short lengths were then connected in series to construct the plumbing systems of Rome, some of which still exist.

Today, tube and tubular products are produced by processes such as casting, extrusion, drawing, piercing, rolling and bending, just to name a few. Tubes and tubular products are manufactured from a host of different materials which include clay, glass, polymers, and various pure and alloyed metals.

4.2 Basic Operations of Three Tube Production Processes:

Although tubes and tubular products may be produced by various methods, this section will focus on the basic concepts of tube extrusion. In this metal forming category, three distinct processes are discussed; those processes are: [2]

- 1) Conventional tube extrusion
- 2) Ugine-Sejournet method of tube extrusion
- 3) Hydrostatic tube extrusion

Each process will be discussed separately.

4.2.1 Conventional Tube Extrusion

Conventional tube extrusion is usually applied to the production of tubes of short lengths. Forward conventional tube extrusion is shown in Fig. 4.3. Here, a billet with a central cylindrical hole is placed into a closed chamber. The ram and mandrel move forward producing high pressure on the chamber side of the die. This pressure forces the material to flow through the die to the low pressure or product side of the die. The mandrel may be "dependent", that is, solidly attached to the ram, therefore having the same forward velocity of the ram. On the other hand, the mandrel may be "independent". This independence may be in the form of a floating mandrel or the mandrel may have a forced forward motion separate from the ram. In the latter case, the mandrel velocity need not equal the ram's velocity.

In some systems, an initially solid billet is hollowed by a punching operation of the mandrel. In all cases, the mandrel is used to control the inner diameter of the tube. The major disadvantage of conventional tube extrusion is the limitation of the mandrel length. Excessively long mandrels can easily sway producing an eccentric tube with uneven wall thickness. [2]

4.2.2 The Ugine-Sejournet Process

The Ugine-Sejournet process was developed as an answer to the problems of extruding steel and other high strength materials. As of World War II, only soft metals had been extruded on an industrial scale.^[2] The problems of excessive friction along the die surface and lubrication at elevated temperatures severely limited steel extrusion.

The use of a lubricant in a viscous condition at the extrusion temperature, and a separation between the lubricant of the chamber and that of the die, are the basis for the Ugine-Sejournet process.^[2] The process begins with a hollow steel billet heated to the extrusion temperature and a uniform coating of glass powder applied to the inner and outer surfaces. The glass powder melts forming a viscous, thin film, lubricant which separates the billet from the chamber wall and mandrel surface. The coefficient of friction is reduced affecting a reduction in the total extrusion force required.

Once the billet has been prepared, it is placed into the extrusion chamber, Fig. 4.4. The extrusion chamber has been previously prepared by the placement of a glass fiber pad on the entry face of the die. The glass pad is forced into a longitudinal contour shape, similar to the metal flow, by the front face of the billet. The hot billet melts a thin layer of this glass pad which will drift along with the outflowing metal and provides a supply of lubricant to separate the die from the extruded product. There is no metal dead zone and the shear effect occurs in the viscous lubricant.

The extruded product is encased in a thin glass layer which is easily removed upon cooling. A variety of glass powders insures a lubricant for almost any specified temperature range.

4.2.3 Hydrostatic Extrusion of Tube

Although still in the experimental stage, the capability of producing a tube by hydrostatic extrusion has been demonstrated by researchers in Japan.^[3]

During hydrostatic extrusion, a hollow billet with the mandrel inserted is placed into a closed chamber. Fluid under pressure provides the motivation force necessary to squeeze the billet between the conical converging die and the mandrel.

The hole in the billet must be larger than the diameter of the mandrel to provide a gap for the fluid medium. This requirement is important for without the gap the high fluid pressure on the outer surface of the billet would force it to warp the mandrel and adhere to it. Mandrel failure by necking and tearing has been recorded when this gap condition was overlooked.

As the billet converges into the die, it squeezes on to the mandrel in the die vicinity. A seal is established by the deforming billet conforming to the die and mandrel preventing the escape of the fluid between the two interfaces. Several variations of the above method for hydrostatic tube extrusion are also possible. These are: (1) the mandrel placed into a fixed position, Fig. 4.5A; (2) the mandrel fixed to the ram, Fig. 4.6; (3) the mandrel supported by the billet and moves forward at the speed of the billet inside the chamber, Fig. 4.7, and a floating mandrel shown in Fig. 4.8.

For a complete description of Tube and Tube Production the reader is referred to Ref. 2.

4.3 Energy - A System's Perspective:

From a system's viewpoint, all metal forming processes require two inputs to produce a product. These inputs are: (1) a raw material and (2) energy. This viewpoint is diagrammatically displayed in Fig. 4.9. Here the raw material can be in the form of strip, rod or sheet, depending on the shape of the final product and the requirement of the particular metal forming process.

An expanded systems view is shown in Fig. 4.10 which shows that for the same part produced, the ultimate raw material is the natural resources of minerals and ores. The finished product of one process then becomes the raw material for the next subsequent process. It also demonstrates that the total energy needed to produce a particular product is the sum of energy requirements of all the processes involved.

The systems view may be contracted or expanded to any degree. Enlargement beyond the secondary metal forming processes, that is, processes designed to produce components of larger products, is beyond the scope of this presentation. Therefore, in Fig. 4.10 the non-metal forming operations will be eliminated. A finished product will be considered to emerge from the secondary metal forming process.

The first two steps in producing a product as shown by Fig. 4.10 are self-explanatory. The raw material, in the form of minerals and ores, is mined and then the sought-after metal is extracted and refined. Primary metal forming includes the production of sheet, rod, plates, strips and any other bulk metal item. These items are then used as the raw material input to secondary metal forming processes. In secondary metal forming processes, the raw material is either drawn, extruded, rolled, forged or machined, into a finished product.

The total energy required to produce a particular item, as stated previously, is the sum of the energy requirement from all the processes. It can now be stated that the raw material needed for any process, requires a certain amount of energy to transform it into a usable state. Therefore, the raw material entering the secondary metal forming process has already consumed a given amount of energy in order to transform it into rods, strips, sheets, etc. This energy will be referred to as the materials' "previously consumed energy."

This case study is directed towards energy conservation at the secondary metal forming process level. At this level, energy savings can be effected in two ways. The first is a transition from a processing

method which is either more energy intensive or requires a larger material input, to one which requires less of both inputs. The second method which can save energy is a reduction of raw material usage thereby reducing the materials' "previously consumed energy." As pointed out above, a change in processing method can reduce material usage. Another means to reduce raw material usage is the elimination of processing defects. The elimination of defects such as central burst, earing and edge cracking, result in a higher yield and lower raw material requirements.

The remainder of this case study will demonstrate that such an energy savings can be realized when cold extrusion is employed over hot forging and machining in the production of a Forward Sun Gear by the Ford Motor Company.

It is shown in this case study, that the cold extrusion process of producing the Forward Sun Gear reduces the amount of raw material required, thereby reducing the materials "previously consumed energy." These substantial energy savings could be augmented if the processing defects of internal cracking, also known as fishskin (shown in Fig. 4.11 for a similar product, an extruded barrel starter) could be totally eliminated. The cracks shown in Fig. 4.11 are typical failure modes in tube and rod making by drawing and forward and backward extrusion. This cracking cannot be tolerated. After a lengthy experimental study^[4], Ford Motor Company eliminated these cracks in their present production. It should be noted that the wall thickness of the forward extruded part is larger than the final component which is machined down to the desired final wall thickness. When a thinner wall was extruded, the internal cracking persisted and could not be prevented.

The cracking on the inside or on the outside during tube extrusion is a common defect that imposes serious manufacturing restrictions and material waste. The problem is similar to the central burst problem which plagued industry until a decade ago. The defect is mainly a processing

defect, namely the defect is produced because of employing the improper independent processing parameters which include:

- i) Reduction in thickness
- ii) Die Angle
- iii) Relative tube thickness to radius
- iv) Lubrication and friction
- v) Length of the land of the die

Speed, temperature, and other parameters also play a role in promoting or deterring this defect.

Again, similar to the problem of central burst, trial and error procedures may produce only temporary solutions for isolated cases. An analytical approach like that provided for the central burst problem may rid the industry from yet another restriction.

4.4 Units, Conversions and Conversion Factors:

As a reference between the various measurement units used in engineering, the following terms have been provided:

Energy per Volume	$\text{kg}\cdot\text{cm}/\text{cm}^3$
Energy	$\text{kg}\cdot\text{cm}$
Weight	kg
Temperature (T)	$^{\circ}\text{C}$
Specific Heat (C_p)	$\text{kg}\cdot\text{cm}/\text{cm}^3/^{\circ}\text{C}$

Some values of energy required to produce a given amount of material (or product) are reported in BTU/TON or BTU/lb. For consistency with the other studies presented here, these values will be reported in $\text{kg}\cdot\text{cm}/\text{cm}^3$. This measurement unit takes into account the density of the material of interest. The following conversions, BTU/TON to $\text{kg}\cdot\text{cm}/\text{cm}^3$, and BTU/lb. to $\text{kg}\cdot\text{cm}/\text{cm}^3$, for steel have been established:

$$1 \frac{\text{BTU}}{\text{TON}} \cdot \frac{\text{TON}}{2000 \text{ lb}} \cdot .555 \frac{\text{kcal/kg}}{\text{BTU/lb}} \cdot 4.267 \times 10^4 \frac{\text{kg*cm}}{\text{kcal}} \cdot .0079 \frac{\text{kg}}{\text{cm}^3} = .035 \frac{\text{kg*cm}}{\text{cm}^3}$$

Therefore:

$$1 \frac{\text{BTU}}{\text{TON}} = .0935 \frac{\text{kg*cm}}{\text{cm}^3}$$

$$1 \frac{\text{BTU}}{\text{lb}} = 187.0 \frac{\text{kg*cm}}{\text{cm}^3}$$

Conversion Factors		
To Convert From	To	Multiply by
BTU	kcal	5.55×10^{-1}
kcal	kg*cm	4.267×10^4
BTU/TON	kg*cm/cm ³	9.35×10^{-2}
BTU/lb	kg*cm/cm ³	1.87×10^2
lb/in ³	kg/cm ³	2.768×10^{-2}

The material property constants used in this study are for an average, low carbon steel. These constants are:

$$\begin{aligned} \text{Density} &= .0079 \text{ kg/cm}^3 \\ \text{Specific Heat} &= 40.3 \text{ kg*cm/cm}^3/^{\circ}\text{C} \end{aligned}$$

4.5 Transition from Hot Forging and Machining to Cold Extrusion:

The Forward Sun Gear F10D and its dimensions are described in Fig. 4.12. Ref. 4 contains a study of the production of such a component by the Ford Motor Company.

The following is a table presenting the different methods for the production of the components and the weight of the raw material associated with each method. The material usage per part for various pro-

cessing methods are:

Desired Cold Formed Blank	851 $\pm$ 2 gm
Actual Cold formed Blank	1023 $\pm$ 2 gm
Hot Forged Blank	1175 $\pm$ 50 gm
Machined from Seamless Tube	1965 $\pm$ 50 gm
Machined from Bar Stock	2395 $\pm$ 50 gm

The present production steps for the sun gear are shown in Fig. 13 and described in Ref. 4. In general, those production steps are:

- 1) Cropping of a slug from bar stock.
- 2) The cropped slug is upset.
- 3) The upset slug is given a spheroidizing anneal.
The anneal is approximately 24 hours at 705°C .
- 4) The upset slug is then coated with zinc phosphate and soap lubricant.
- 5) The upset slug is backward extruded to form a cup.
The bottom of the cup being punched out in a subsequent operation forming a tube.
- 6) The tube is forward extruded over a mandrel producing the basic shape.
- 7) The basic shape is given a normalizing anneal for 8 hours at 915°C.
- 8) The basic shape is now machined to final dimensions.
- 9) The gears are cut into the part.

If the steps 1 through 8 were replaced by a single forward extrusion from bar stock, the component's weight would equal the Desired Cold Formed weight of 851 gm. In comparing one process over another, the Desired Cold Forming component weight will be considered the "ideal weight." All components produced by other processes will be compared to the "ideal weight."

"Previously consumed energy" was previously defined as that energy needed to transform a raw material into a usable state. The production of the Forward Sun Gear by most methods begins with cylindrical rod. The energy required to produce that rod from minerals and ores is the "previously consumed energy." It takes approximately 29,000,000 BTU's to produce 1 ton of steel. This is the energy which is needed to produce steel rod (also sheet, plate and strip) which is the raw material of the Forward Sun Gear.

The total energy required to produce the gear would then be sum of: 1) "previously consumed energy" per part, 2) the secondary metal forming process energy, and 3) the annealing energy of any required anneals. In this case study (Sec. 4.0), different processing methods are compared. The savings in material and elimination of anneals achieved by each process will be determined. The basis for the comparison is the energy content in the material saved and the savings in annealing energy.

4.6 Energy Comparison of Various Production Methods of a Forward Sun Gear

In the units section it was shown that 1 BTU/TON is equivalent to .0935 kg-cm/cm³. Therefore, 29,000,000 BTU/TON of steel is equal to 2.71×10^6 kg-cm/cm³. The calculated "previously consumed energy" per part of the Forward Sun Gear produced by cold extrusion would be:

$$.851 \text{ kg.} \cdot \frac{1 \text{ cm}^3}{.0079 \text{ kg}} \cdot 2.71 \times 10^6 \frac{\text{kg} \cdot \text{cm}}{\text{cm}^3} = 2.91 \times 10^8 \text{ kg} \cdot \text{cm}$$

The "previously consumed energy" for each method and component weight is shown in Exhibit 4.1. When the value of the "previously consumed energy" for each method is compared to the ideal method energy, that is, the "previously consumed energy" for the Desired Cold Formed Blank, the percent energy savings results. The percentage of energy saved, based on "previously consumed energy" is also shown in Exhibit 4.1. Here it is demonstrated that a 27.4% energy savings can be realized if the Forward Sun

Gear is produced by cold extrusion rather than hot forged. The actual savings are higher because the annealing energy was not included in Exhibit 4.1.

A first order approximation of the annealing energy can be obtained from the following equation:

$$W_{Ai} = C_p \cdot \Delta T$$

where:

W_{Ai} is the ideal annealing energy

C_p is the specific heat of steel

ΔT is the change in temperature

For the spheroidizing anneal needed by the gear, if hot forged, the annealing energy is:

$$W_{Ai} = 40.3 \frac{\text{kg} \cdot \text{cm}}{\text{cm}^3 \cdot ^\circ\text{C}} (705^\circ\text{C} - 20^\circ\text{C})$$

$$W_{Ai} = 27605.5 \frac{\text{kg} \cdot \text{cm}}{\text{cm}^3}$$

This value would increase as the annealing furnace efficiency decreased. Exhibit 4.2 represents the annealing energy of both spheroidizing and normalizing anneals for various furnace efficiencies.

Now a comparison of process methods can be made using both the "previously consumed energy" and annealing energy, if any.

It should be noted that each metalforming process would require a specific alloy material in order to better meet the sun gear part specifications. The alloy used in one process may not demonstrate its optimum properties when used in another metalforming process. It may be possible, therefore, to choose an alloy for the cold extrusion of the Forward Sun gear which would not require any annealing operations and still meet the required performance standards of the part, whereby properties achieved through strain hardening will equal those reached otherwise by heat treatment. In that case, the energy requirement by cold extrusion would equal the "previously

consumed energy". A tabulation of the sum of "previously consumed energy" and annealing energy for various production processes is shown in Exhibit 4.3. Exhibit 4.3 also shows the total energy savings when the various process methods are compared to cold extrusion.

The desired cold forming process consumes the least energy of all alternatives considered. Cold forming is, therefore, considered the reference basis for the calculated savings. The excess material (and, hence, input energy) and anneal energy consumed by each process over that of cold forming is determined.

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EXHIBIT 4.1

ENERGY SAVED BASED ON MATERIAL CONSERVATION COMPARED WITH DESIRED COLD FORMED BLANK

Processing Method	Part Weight		Previously Consumed Energy per Part		Savings per Part
	lbs	kg	BTU · 10 ⁶	kg*cm · 10 ⁸	%
Desired Cold Formed Blank	1.87	.851	2.72	2.91	
Actual Cold Formed Blank	2.25	1.023	3.27	3.50	16.8
Hot Forged Blank	2.59	1.175	3.75	4.03	27.4
Machined from Seamless Tube	4.33	1.965	6.28	6.74	56.6
Machined from Bar Stock	5.27	2.395	7.65	8.21	64.5

EXHIBIT 4.2 ANNEALING ENERGY - VOLUME BASIS

TYPE OF ANNEAL	Temperature [°C]	Time [hrs.]	Furnace Efficiency	ANNEALING ENERGY Total Anneal Energy kg*cm/cm ³
Spheroidizing	705°	24	100	27605.5
			50	55211.0
			7	394364.2
Normalizing	915°	8	100	36068.5
			50	72137.0
			7	515264.2

EXHIBIT 4.3 TOTAL ENERGY SAVINGS PER PART *

	Processing Method	Previously Consumed Energy [10 ⁶]	ENERGY [kg*cm]			Total Energy [10 ⁶]	SAVINGS %
			Furnace % Efficiency	Spheroidizing	Normalizing		
4.16	Desired Cold Formed Blank	291.0	-	-	-	291.0	-
	Actual Cold Formed Blank	350.0	100	3.57	4.6	358.0	18.7
			50	7.14	9.34	366.0	20.4
			7	51.04	66.71	467.0	37.6
	Hot Forged Blank	430.0	100	-	5.36	435.3	33.1
			50	-	10.72	440.7	33.9
			7	-	76.63	506.6	42.5
	Machined From Seamless Tube	674.0	100	-	8.97	682.9	57.3
			50	-	17.9	691.9	57.8
			7	-	128.16	802.1	63.7
	Machined From Bar Stock	765.0	100	-	10.9	775.9	62.4
			50	-	21.8	786.8	63.0
			7	-	156.2	921.0	68.4

*note: The above energy values do not include the actual process energy, i.e. the energy to machine, forge, or extrude the part. The material energy content value is based on energy already spent on the material prior to the metal forming operation. See text for details.

EXHIBIT 4.4 COMPARATIVE PROCESSING

PROCESSES

PERCENTAGE OF ENERGY SAVED

COMPARED

Machined from Seamless Tube

compared to

13.4

Machined from Bar Stock

Hot Forged Blank

compared to

40.2

Machined Seamless Tube

Actual Cold Formed

compared to

13.1

Hot Forged Blank

FIG.4.1 ANCIENT LEAD PIPE LINE .

FIG.4.2 TUBE DRAWING IN ANTIQUITY. (SPECULATIVE)

FIG.4.3 TUBE MAKING FROM HOLLOW BILLETS.

FIG.4.4 STEEL TUBE EXTRUSION BY SEJOURNET.

(a) CONVENTIONAL FIXED MANDREL

(b) MANDREL FIXED TO CONNECTING CYLINDER

FIG.4.5 FIXED MANDREL HYDROSTATIC EXTRUSION OF TUBE

FIG.4.6 MANDREL - RAM SOLID ASSEMBLY FOR THE HYDROSTATIC EXTRUSION OF A TUBE .

FIG. 4.7 CONVENTIONAL TRAVELING MANDREL FOR THE HYDROSTATIC EXTRUSION OF A TUBE. (FIG. 1 OF REF. 13)

FIG.4.8 FLOATING MANDREL FOR THE HYDROSTATIC EXTRUSION OF A TUBE

FIGURE 4.9 SYSTEMS VIEW - A SINGLE SECONDARY METALFORMING PROCESS

FIGURE 4.10 ENLARGED SYSTEMS VIEW - PART PRODUCTION

FIG.4.II BARREL STARTER.

FIG.4.13 PRODUCTION STEPS OF SUN GEAR.
(COURTESY OF FORD MOTOR CO.)

CONCENTRICITY:
A TO B WITHIN .005 T.I.R.
A TO C WITHIN .010 T.I.R.

PART NORMALIZED AFTER
MACHINING.

FIG.4.12 FORWARD SUN GEAR. (COURTESY OF FORD
MOTOR CO.) 4.29

5.0 HOT VERSUS WARM FORGING

OF A CHRYSLER PINION GEAR

5.1 Energy Requirements for Forging:

Various metal forming methods can be replaced by alternate forming techniques, resulting in considerable energy savings. This case study deals with the conventional metal forming process of forging. The focus of the investigation is to select a forging temperature where total energy consumption is minimized and also to show that this optimal temperature is room temperature.

The energy necessary to upset a forging is a function of the flow strength of the workpiece, the specific heat, percent reduction, rate of deformation, and the efficiency of the press. Of the above list, the percent reduction, the rate of deformation and, possibly, press efficiency can be controlled by the manufacturer. The specific heat and flow strength are characteristics of the forging material and are functions of temperature. Therefore, the bottom line in forging energy requirements may be said to be a function of temperature. The energy needed for the heating of the workpiece is dependent on the specific heat of the material, the volume of the piece, and the efficiency of the heating unit. The sum of these two energies, deformation energy and heating energy, gives the total energy needed for forging.

The energy required by the press decreases as the working temperature increases while the energy required for heating the workpiece shows the opposite relationship, that is, the heating energy demand increases with higher temperature. Summing these two values gives the total energy needed for forging. This summation will have a minimum value at some temperature, (see Fig. 5.1). This study shows that the minimum energy occurs at an operating temperature near or at room temperature.

While the stated goal may be the forming at room temperature, several factors may make this goal hard to achieve. Mainly due to limited ductility the component may fracture (split) at excessive cold deformation. Then

higher forming temperature may be required. Constant technological advances are making it possible to cold form more and more components which previously were warm or hot formed. However, in practical industrial environment, it is found on many occasions that higher forming temperatures are desirable. For example, when controlled cooling is practiced to eliminate a heat treating operation.

5.2 Production of A Rear Axle Drive Pinion:

The Chrysler Corporation case study is an example of a metal forming operation that used the preceeding procedure for determining the optimal temperature for minimizing energy consumption.

The part under consideration is a Rear Axle Drive Pinion (Fig. 5.2). The part is made from SAE 4422 steel with the following chemistry percentages:

C	Mn	Mo	P	S	Si
.2-.25	.70-.90	.35-.45	.04	.04	.20-.35

The properties of an appropriate steel are listed below:

- melting point 1520°C
- yield strength 2500 kg/cm^2 (35,561 psi)
- ultimate tensile strength of cold worked (piano) wire 25000 kg/cm^2 (355,619 psi)
- specific heat $40.3 \text{ kg*cm/cm}^3/^{\circ}\text{C}$
- specific gravity 7.86 gm/cm^3

The method previously used to make the part was the machining of a hot forging. This method resulted in large material losses which can be interpreted as energy losses by considering the materials "previously consumed energy" as described in Sec. 4.3. Heat treatment is presently needed to bring the piece within specifications for strength.

At present, the piece is made by the sequence of steps shown in Fig. 5.3. The size of the blank is accurately determined through volume constancy calculations, thus eliminating some material waste, except for slight machining and final grinding and polishing. The first step is a forward extrusion which is done at room temperature. The second step is a forging operation during which the end of the shaft is upset to form the head of the piece. The temperature at which to perform the forging of the head was the object of this study.

The first step in determining the total energy consumed was to find the amount of energy needed to heat the piece to various temperatures. It was assumed that all the energy put into the piece went into the heating of the head and none into the shaft. Actually the shaft would act as a heat sink. This assumption, like others to follow, is biased toward the use of elevated temperatures, thus assuring that any conclusions will be based on conservative calculations. Using the equation for heating described earlier (Sec. 3), the energy required to heat the piece to room temperature is obviously zero, and $59644 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$ at a temperature of 1500°C . The values are linear between these two points. (This calculation assumes that the heating process is 100% efficient).

The energy for forging can be determined from the flow stress of the material. A reduction of 61% percent is used based on the change in height, assuming volume constancy. The energy needed for forging at room temperature (20°C) is $8018 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$. At 1500°C the energy required drops to $107 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$. This function is also linear between these two points. Since the values for heating requirements and forging requirements are in the same units, they can be summed to give the total energy requirements at different forging temperatures. At 20°C the total energy needed for forging is only the forging energy since no heating is done. This value is $8018 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$. At a temperature of 1500°C the total energy is $59751 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$, the sum of the heating and forging energy.

For most applications, the optimal forging temperature accounting only for heating and forming energies, and from an energy conservation point of view, is room temperature. In the present case, higher than required forming temperatures are used so that the part can be control cooled after forming, thus eliminating the need for isothermal annealing.

5.3 Energy Calculations and Energy Savings:

The amount of energy that could theoretically be saved by switching from the hot forging of the entire piece to the newer method of cold and warm forming is demonstrated below and shown in tabulated form as Exhibit 5.1.

When the entire piece was hot forged at 1000°C , the energy required to heat the piece to this temperature was $1.6 \times 10^7 \frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}$. The energy saved by eliminating material waste is calculated on the next page.

The previous workpiece had to be oversized to allow for the machining of the workpiece to proper dimensions. The reduction in weight is .9 kg. The energy needed to produce 1 ton of steel is approximately 29×10^6 BTU. [6] This is equivalent to 3.19×10^4 BTU/kg. Thus the reduction of .9 kg is an energy saving of 2.88×10^4 BTU, which is equivalent to $3.09 \times 10^8 \frac{\text{kg*cm}}{\text{cm}^3}$.

The amount of energy that is saved by switching to a cold and warm forming is calculated below.

If the head of the piece was previously forged at 1000°C , the energy required to form the end of the shaft at this temperature was $4.23 \times 10^4 \frac{\text{kg*cm}}{\text{cm}^3}$ (energy to heat plus energy to deform). Upon switching to cold forging of the shaft alone, the total energy required is reduced to $0.8 \times 10^4 \frac{\text{kg*cm}}{\text{cm}^3}$ (energy to deform) which is a savings of $3.43 \times 10^4 \frac{\text{kg*cm}}{\text{cm}^3}$ or 76%.

6000 BTU ($6.45 \times 10^7 \frac{\text{kg*cm}}{\text{cm}^3}$) was conserved by eliminating the post forming heat treatment.

These four calculations represent the energy savings possible by switching to alternate metal forming techniques and the energy saved by a reduction in the forging temperature to room temperature. A more complete listing of the energy savings and monetary savings is shown as Exhibit 5.2:

5.4 Reduced Temperature Forging:

5.4.1 Advantages

The energy saving is obviously an important result of performing the forging operation at low temperatures. However, other benefits of cold forging also become evident and should be noted.

1. Better Dimensional Stability : Forging at elevated temperatures creates the problem of determining the dimensions of the final product. The expansion that occurs upon heating coupled with the spring back encountered in forging and the oxide formation, all make determination of dimensions quite a problem. To counteract the limitations of hot forging, the piece is made larger than necessary and machined to final dimensions.

Cold forging eliminates the change due to temperature (except the temperature rise from internal heating) and also the formation of detrimental oxide layers. Therefore, tighter control of the piece's dimensions can be achieved. Because of the more accurately sized piece and better surface finish, less final grinding is required, a labor intensive step, and the production cost is lowered and less material is wasted.

2. Longer Tool Life : Hot forging requires die material that can function at the temperature of interest. Elevated temperatures have the same effect on the die material as on the workpiece, that is, lowering of the flow strength. To compensate for this strength loss, higher temperature, higher alloy steels have been developed for use in dies. Cold forging is associated with higher tool loads but eliminates the temperature problem, allowing the designer of the die an option. The die can be made out of the more expensive material, high alloy, carbide steel and require replacement less often than they would have at an elevated temperature. The option would be to use a cheaper steel and still have the same life as the expensive die at elevated temperatures. Part of this extended life comes from the fact that in elevated temperature use, the die experiences fatigue not only from the stress applied, but also from thermal stress. The hot workpiece heats the die in a short period of time causing expansion leading to stress and also loss of dimensional control. Cold forging does not have this problem.

3. Elimination of Postforming Heat Treatment: The deforming the piece at a cold temperature offers the advantage that the piece undergoes work-hardening. This can occur to an extent where postforming heat treatment may become unnecessary. These heat treatments, which are needed for hot forgings, require large amounts of energy, man-hours, and floor space. All of the above are expensive and slow down the rate of production. Furthermore, cheaper steel is used for cold formed parts that reach their strength by strain hardening, rather than the more expensive steels required when the strength is reached by heat treatment. Cold forging offers cost reductions along with the energy savings.

5.4.2 Limitations

1. Cold forging presents some difficulties to the designer/engineer. Most obvious is the fact that much larger forces are necessary to deform the workpiece if it is not heated. This means that larger presses are required. Large forgings might be technically impossible to work cold because of the limitation of the press size. The two largest hydraulic presses in the United States are rated at 50,000 tons.^[6] They are located at the Air Force plants operated by Alcoa in Cleveland, Ohio, and by Wyman-Gorden in North Grafton, Massachusetts. Such large presses and other types of impact presses reduce the press limitation problem caused by reduced temperature deformation.

2. The ductility of the workpiece is the biggest deterrent to the use of cold forging as to even wider application in metalforming. Hot forging makes use of the fact that at elevated temperatures the material becomes more ductile, reducing the brittle fracturing that can occur during forging. The actual transformation from brittle to ductile does not occur at a particular temperature as it does for the glass transition of some materials. The transition in forging is dependent on the amount of deformation, the rate of deformation as well as the material itself. Each material has to be evaluated to determine the combination of parameters where brittle cracking does not occur. A balance has to be reached where energy savings are maximized while brittle cracking is still eliminated; this trade-off will probably result in selection of a forging temperature which is not the most optimal, from an energy standpoint but a slightly elevated temperature to eliminate the brittle cracking problem. Metalworking Under Pressure (MUP) is a possible solution to the brittle cracking problem.^[7]

5.5 Conclusions for Hot versus Warm Forging:

The selection of the proper temperature for forging, from an energy conservation point of view, results in considerable energy savings. Actual heating energy waste is much higher due to inefficiencies of the heating

furnaces, as studied in Sec. 3.3. These savings stem from many factors including: reduced heating demand, reduced material waste, possible elimination of post-metal forming heat treatment, and reduced floor space. Other advantages to using reduced temperature forging include better dimensional stability, better surface finish, longer die life, and overall reduction of fabrication costs.

The ductility of the workpiece is one limitation to cold or low temperature forging. The size of the press needed is another factor that must be considered in the selection of forging temperature. If these limiting factors can be overcome, reduced forging temperature can result in considerable energy and material savings, resulting in lower production costs.

In recent years better understanding of deformation processes, new powerful compact presses and better tool materials all lead to a more predominant role of cold forming as the selected process.

EXHIBIT 5.1 ENERGY CALCULATIONS - TABULATED

Savings Category	kg/part	BTU/part	Cal./part	$\frac{\text{kg}\cdot\text{cm}}{\text{cm}^3}/\text{part}$
Material savings	.9	2.87×10^4	7.26×10^6	3.09×10^8
Elimination of hot forging the shaft	-	6.68×10^2	1.68×10^5	7.18×10^6
Elimination of hot forging the head	-	8.64×10^2	2.18×10^5	9.29×10^6
Elimination of post- form heat treatment	-	6.00×10^3	1.51×10^6	6.45×10^7
Total	.9	3.63×10^4	9.15×10^6	3.9×10^8
Total for 1000 parts	9.0×10^2	3.63×10^7	9.15×10^9	3.9×10^{11}

It takes 3.19×10^4 BTU/kg to produce steel, up to and including the casting operation

1 BTU = 252 Cal.

1 Cal. = 42.665 kg $\cdot$ cm

EXHIBIT 5.2 LISTING OF ENERGY SAVINGS

Saving of material

Eliminating of chip forming operations.

- turning
- boring
- facing
- chamfering
- cut off
- rough grinding

Eliminating heating for hot forging

Elimination of post-form heat treatment

Reduction of needed floor space

Monetary Savings *

Reduced energy costs

Reduced capital expense

Reduced material costs

Reduced labor costs

Reduced building costs (construction and maintenance)

Reduced tooling costs

Increased production rate

* The greatest potential savings arises from reduction of overhead.

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FIG.5.1 ENERGY VS. TEMPERATURE FOR FORGING.

FIG.5.2 PINION GEAR .

BLANK

FIRST STEP

SECOND STEP

FIG.5.3 PRODUCTION STEPS.

FIG.5.4 ENERGY FOR HEATING.

FIG.5.5 ENERGY FOR FORGING.

FIG.5.6 TOTAL ENERGY.

6.0 ELIMINATION OF PROCESSING DEFECTS AS A MEANS OF

ENERGY CONSERVATION

This case study considers the energy conserved by the elimination of one form of processing defects. The energy savings that were obtained, as a result of the elimination of central burst, are detailed. The prevention of central burst came only after a concentrated research effort. It is likely that other processing defects can also be eliminated, thereby effecting an energy savings, if a similar concentrated analytical effort is put forth.

6.1 Central Burst Defects:

The investigation of the central burst defect began in the 1920's when Harris^[1] and Remmers^[2] briefly described the defect. The first extensive study on central burst was conducted by H. C. Jennison^[3] in 1930. Jennison stated that the properties of the work material have "too often and unjustly been held responsible for these particular defects (chevrons) ...". He proposed that "cup and cone wire (namely wire with a chevron) and satisfactory wire without any defect may be produced at will with the same dies on the same wire machine using the same bar of copper". Jennison reported that he had demonstrated this achievement, repeating the results "indefinitely". Although his 'criteria' were qualitative, he was the first to observe the significance of geometrical variables in preventing these defects. He stated his observations clearly, "... the greater the angularity of the die and the lighter the reduction in drawing, the greater will be the tendency toward cup and cone conditions". (See Jennison, pp.9, end of 2nd paragraph).

By the sixties, Jennison's work was nearly forgotten. Industry firmly believed that the cause of central burst was faulty work material.^[4] Thus, unreasonable demands were imposed on composition and ingot uniformity. Other methods used to try to prevent the defect were annealing prior to drawing or extruding or changing the process variables randomly.

Most industrial firms facing the central burst defect would not discuss or publicize their problems, and very little information about the defect appeared in the literature. One company experiencing problems involving central burst was an automotive corporation. Forming the connecting linkage between the steering wheel and the front wheels of an automobile involved taking small reductions on material that was extensively cold-worked, and, therefore, strain hardened. These conditions favor the formation of central burst and the defect did occur in the linkage. These defects occurred in about 10% of the parts made; however, because these defects are internal and do not appear on the surface, the defective parts were unknowingly installed. It was not until a tragic auto accident occurred, while a car with the defective part was being driven, that the defect was discovered and recognized as the cause of failure.

Having no means to prevent the defect from forming, the company embarked on a 100% inspection procedure using ultra-sonic detectors that rejected any part with central burst. This procedure proved very expensive, primarily because of increased handling and extra working stations. Furthermore, up to 10% of the products were rejected resulting in high scrap cost of finished products. After using 100% inspection with its increased time, labor and cost, it was decided to attempt to pursue a defect prevention program. The automotive company wanted to eliminate the defect altogether rather than produce defective parts which have to be inspected and rejected.

In accordance with the belief common to industry, they thought that the work material was causing the central burst defect. However, the supplier of the material did not believe its steel was to blame. To prove their point, the company asked Betzalel Avitzur of Lehigh University to investigate why central burst was occurring.^[5]

Dr. Avitzur began his investigation in 1966, to be later joined by his student Z. Zimmerman. The problem was attacked analytically^[6], and quantitative criteria for the prevention of central burst were developed.

When the combination of die angle and reduction lies above the respective constant friction line, in Fig. 6.1, central burst in a homogeneous Mises material is expected. Strain hardening was proposed as a deterrent for this defect^[6], and an analysis of its effect was performed.^[7]

This criterion takes strain hardening into consideration as well as friction. Any forming operation for which the combination of die semi-cone angle and reduction in area lies to the left of the appropriate lines in Fig. 6.1, will be in the region free from central burst. The strain hardening capacity effect, presented in three groups : non-strain hardening, moderate strain hardening, and high strain hardening, is also shown.

Dr. Avitzur's criterion has been used successfully by American industry for years, see Fig. 6.2.^[9] It is also being used in England, Germany, Japan, France, Brazil and other countries. For example, see Ref. 10, 11 and 12.

Thus, the quantitative criteria presented by Jennison in 1930, and vigorously analyzed in 1966, has resulted in qualitative criteria that enable the central bursting defect to be prevented.

6.2 Basic Concepts:

6.2.1 An Overview of Flow Through Conical Converging Dies:

A brief treatment of material flow through conical converging dies is given here to familiarize the reader with the processes discussed. A complete discussion of material flow through conical converging dies and related subjects of friction, die angle and material reduction, can be found in Refs. 13, 18 and 23.

The forming of metal, both hot and cold, by pushing or pulling through conical converging dies, finds wide application in such processes as wire drawing, conventional extrusion and hydrostatic extrusion. Fig. 6.3 shows a typical die-billet setup for such processes. The billet is forced through the conical portion which has an arbitrary semi-cone angle α , and its radius is reduced from R_0 , the original radius, to R_f , the final radius, determined by the size of the cylindrical portion of the die, L , called the bearing.

The length L of the bearing is finite (not zero) because of die manufacturing requirements, and also to assure uniformity and minimize increase in final diameter due to die wear. In drawing, the stress σ_{xf} provides the required power, while σ_{xb} may or may not be zero. For extrusion, the extrusion stress σ_{xb} provides the power, while σ_{xf} may or may not be zero.

The drawing of non-ferrous metals into wire is an ancient craft but extrusion is relatively recent. The first controlled experiments in hot extrusion were carried out in 1931 by Siebel and Fangmeier, Sachs and Eisbein, and Pearson and Smythe (as reported in Ref. 14). The hot extrusion of steel became feasible with the introduction of glass lubrication in 1941.¹⁵ During World War II, the development of a phosphate-base for lubricants made possible the cold extrusion of steel. See Ugine-Sejournet method, Sec. 4.2.2. in Basic Operations of Three Tube Production Processes, Sec. 4.2, for a complete description of this process.

The semi-cone angle of the die (α in Fig. 6.3) has a pronounced effect on the total force needed to form a metal, on the flow patterns, and on the internal and external soundness of the extrusion or drawing. Fig. 6.4 summarizes this effect for drawing stress (σ_{xf}) vs. semi-cone angle (α) (See Ref. 17). In the sound flow region of Fig. 6.4, the drawing stress changes continuously with semi-cone angle and exhibits a minimum at some cone angle designated as the optimal cone angle (α_{opt}).

Excessive cone angles may cause the metal to shear within itself and form its own cone angle for the reduction. When this happens, the metal is said to have formed a "dead zone" because that part of the metal forming the new channel no longer flows and the new angle is known as the dead zone cone angle. For any semi-cone angle between α_{cr1} and α_{cr2} , in Fig. 6.4, this dead zone angle will form. The dead zone cone angle is constant for each percent reduction, and the drawing stress (σ_{xf}) in this region between α_{cr1} and α_{cr2} remains constant. Beyond α_{cr2} , the die acts much like a cutting tool in that it shaves the billet, and the drawing

stress drops off with sharper die edges.

Fig. 6.4 also shows an overlapping region between sound flow and dead zone formation domains. This region is formed by a few unique combinations of reduction, friction, cone angle and prior straining. Here the material may undergo internal ruptures forming defects called central burst. Special attention to central burst will be given in later sections.

The analysis of flow through conical converging dies leads to the previously mentioned relationships shown diagrammatically in Fig. 6.4. The mathematics presented here are limited to a few of the more important equations. A complete treatment may be found in Ref. 18. The mathematical treatment, based on the upper bound approach may be studied in Ref. 29.

The study of material flow through conical converging dies is based on the choice of a kinematically admissible velocity field. This approach is shown in Fig. 6.5. The material in Fig. 6.5 is divided into three regions in which the velocity field is continuous. In zones I and III, the velocity is uniform and has an axial component only. In zone I the velocity is designated v_o while in zone III the velocity is shown as v_f .

Due to volume constancy,

$$v_o = v_f \left(\frac{R_f}{R_o} \right) \quad \text{Eq. (6.1)}$$

In zone I deformation has not yet begun. It includes the incoming rod, separated from the deforming zone II by the surface Γ_2 . Surface Γ_2 is spherical, with a radius r_o with the origin at the apex (o) of the cone of the die. Zone II, the zone of deformation, is bounded by the surface of the die, which is a cone of an included angle 2α , and by two concentric spherical surfaces Γ_1 and Γ_2 . The surface Γ_2 is the spherical boundary mentioned above between zones I and II. The spherical surface Γ_1 of radius r_f with the origin at the apex (o) of the cone separates zone II from the emerging product of zone III. In zone II the velocity is directed with

cylindrical symmetry towards the apex (o) of the cone.

In the spherical coordinate system (r, ρ, θ) , the velocity components are

$$\begin{aligned}\dot{U}_r &= v = v_f r_f^2 \frac{\cos \theta}{r^2} \\ \dot{U}_\theta &= \dot{U}_\rho = 0\end{aligned}\quad \text{Eq. (6.2)}$$

The velocity field of Fig. 6.5 and Eqs.(6.1)and(6.2)was used in Refs. 18 and 19 for the prediction of the distortion of the deformed product. This distortion can be studied experimentally by the visio-plasticity method. The billet is split in two along its axis of symmetry. Grids are marked parallel and normal to the axis of symmetry. The billet is then reassembled and drawn or extruded. In Ref. 19 the effect of reduction and cone angle on the distorted grid in hydrostatic extrusion was studied. Cone angles varied from $5^\circ < \alpha < 40^\circ$ and reductions were made from $5\% < r < 50\%$. Comparison between the experimental results and the theoretical prediction that stems from Eqs.(6.1)and(6.2), (Refs. 17, 18) are given in Fig. 6.6. The abscissa of Fig. 6.6 is the relative radial distance from the center line. The ordinate is the relative distorted distance, after deformation, of the grid which originally was a straight line normal to the axis of symmetry. To make it possible to present results from different reductions on the same curve, the relative distance on the ordinate is divided by the respective value of $\left(\frac{R_o}{R_f}\right)^3 - 1$ for each reduction. The parameter becomes the cone angle α . One can see that increases in either reduction or cone angle or both cause an increase in distortion. For further details on distortion, strain hardening and effective strain rate, see Refs. 17, 18 and 28.

The same velocity field (Eqs.(6.1)and (6.2)was used with the upper bound approach (Refs. 17 and 20) to evaluate the drawing or extrusion stresses. It was there shown (17, 20) how the internal power (ideal and distortion), together with friction losses, dictates the required forces.

Fig. 6.7 shows how the three interacting parameters of ideal deformation, redundant work (shear resistance), and friction losses vary with die

semi-cone angle (α) to produce a minimum on the total resistance curve for drawing. The ideal deformation term ($\dot{W}_i$) considers only the power required to reduce the diameter of a billet, disregarding distortion and friction losses. Thus, ($\dot{W}_i$) varies little with increasing die angle. The shear resistance term ($\dot{W}_s$) considers the power needed to produce a specific amount of distortion and shows an increase with cone angle. In drawing or hydrostatic extrusion, the power losses due to friction ($\dot{W}_f$) come about as the billet passes over the die wall. For small cone angles, the contact area between die and billet is large, and, therefore, the friction losses are large. But the larger the cone angle, the less the die-billet contact area and the lower the relative speed of the billet over the contact area and the friction losses decrease. When the curves for all three of these interacting effects are added to give the curve for total resistance to deformation, there is, for any one set of friction and reduction conditions, a minimum in the reduced stress at one particular semi-cone angle.

The angle which minimizes the required stress is known as the optimal semi-cone angle (α_{opt}). In Fig. 6.7 the ordinate is relative drawing stress $\frac{\sigma_{xf}}{\sigma_0}$, where σ_{xf} is the drawing force divided by the cross-sectional area of the product, and σ_0 is the flow stress of the product. Fig. 6.7 is plotted in this manner in order to make it dimensionless, and, therefore, applicable to any material. If the ordinate was simply drawing stress (PSI) or even force (lbs.), the result would be the same, and the position of the optimal angle (under the same set of conditions) would remain the same. In that hydrostatic extrusion involves no billet-container contact, it is similar to rod or wire drawing, and the above arguments apply equally well.

Although friction must enter as a consideration during material flow through conical converging dies, only a brief treatment will be given here. A full analysis can be studied in Ref. 23. That study, which utilized von Mises' yield criterion to define friction, developed the following method for determination of the coefficient of friction for any particular processing condition of drawing extrusion and rolling.

According to von Mises' yield criterion definition of friction, the maximum amount of shear that an ideally plastic, non-strain hardening material can undergo without rupture, may be given by:

$$k = \frac{\sigma_0}{\sqrt{3}} \quad \text{Eq. (6.3)}$$

where k is the maximum shear stress and σ_0 is the yield stress in tension. Using this equation, the frictional resistance to flow (τ), when forming metal, can be expressed as

$$\tau = m \frac{\sigma_0}{\sqrt{3}} \quad \text{Eq. (6.4)}$$

where m , the friction factor, becomes the proportionality constant. Thus, the maximum possible friction is denoted by $m = 1$, and no friction by $m = 0$. This way of looking at friction gives an accurate physical picture of what is actually happening in a metal forming process, and, in addition, is easy to handle mathematically.

Wistreich^[8] measured friction by drawing copper wires through a split die and measuring the force needed to keep the die halves together. Yang^[22] used a somewhat different technique for determining friction values in the drawing of aluminum and zinc wires. He measured die pressures by drawing through a split die enclosed in a die plate equipped with a system of sensitive strain gages. By electrically monitoring the strain gages during the drawing operation, he was able to measure die pressures. While these techniques are highly accurate, they do not readily lend themselves to use on production equipment.

The upper bound on power approach has been used to develop a method that allows experimental determination of the friction factor (m) with production equipment with little or no additional instrumentation.

The equation which is essential to the technique is, for the

friction factor,

$$m = \left\{ 2 \frac{1 - \alpha_{\text{opt}} \cot \alpha_{\text{opt}} + \sqrt{3} (\sin \alpha_{\text{opt}})}{\ln \left(\frac{R_o}{R_f} \right)} \left[\sqrt{1 - \frac{11}{12} \sin^2 \alpha_{\text{opt}}} - (\cos \alpha_{\text{opt}}) f(\alpha_{\text{opt}}) \right] \right\} \quad \text{Eq. (6.5)}$$

where α_{opt} (in radians) is the optimal cone angle to minimize drawing (or extrusion) force, R_o is the original billet radius, R_f the final billet radius, and $f(\alpha_{\text{opt}})$ is a function of the semi-cone angle resulting from the technique used to derive the equation. An expression for the Coulomb coefficient of friction may also be obtained from this analysis. It can be shown that for small cone angles ($\alpha < 45^\circ$), $f(\alpha) \approx 1$ and m can be quite closely approximated by:

$$m = \frac{\frac{2}{3} \alpha_{\text{opt}}^2}{\ln \left(\frac{R_o}{R_f} \right)} \quad \text{Eq. (6.6)}$$

The friction factor can now be evaluated through either Eq. (6.6) by an experimental determination of the optimal cone angle.

Fig. 6.8 shows the variation of relative drawing stress $\frac{\sigma_x f}{\sigma_o}$ with semi-cone angle for a number of percent reductions in area ($r\%$) and for a single value of friction ($m = 0.03$). The back tension (σ_{xb}) and the die land (l) are assumed to be zero. Equations describing Fig. 6.8 may be found in Refs. 17 and 20.

Assuming the friction factor to be constant over the range of reductions and for one particular set of dies and lubrication conditions, the analysis shows that higher values of friction will shift the curves in Fig. 6.8 and their minimums up and to the right. For lower values of friction, the reverse is true. In addition, the curve for each higher reduction exhibits a minimum at successively higher values of the semi-cone angle. This type of behavior has been noted by many in-

investigators, and in particular by Wistreich^[21] and Pugh.^[24]

In order to obtain the experimental curves corresponding to the theoretical curves of Fig. 6.8, all that is needed is a set of dies, ranging from small to large cone angle, and some means of measuring the force needed to draw or extrude the material. The force can be measured with a set of calibrated strain gages mounted on the drawing or extrusion ram, through calibration of an accurate hydraulic pressure gage, or by some other relatively simple method. Billets of various initial diameters are prepared. Drawings or extrusions are made over a range of cone angles and for a number of reductions, and the force required is recorded for each combination of reduction and cone angle.

The curve for each reduction is then plotted for force, stress, or relative stress (the ordinate can be any of these for our purposes) vs. semi-cone angle. It is unlikely that any of the dies will have the cone angle which will produce the minimum stress. Therefore, a curve is drawn connecting the minimums for each reduction, and a value for α_{opt} is read off the abscissa where this curve of minimum stress crosses the curve for each reduction. Eq. (6.5) or Eq. (6.6) is then used to calculate m values for each reduction, the m values are averaged, and the average m value ($\bar{m}$) is taken to be the friction factor for this particular set of process conditions.

This procedure has been applied in Ref. 23 to various sets of experimental data for drawing and extrusion. Fig. 6.9 shows the result of an experiment conducted by Evans and Avitzur, Ref. 13, on the drawing of low-carbon steel (< 0.02 wt.%C). In any application of this technique, the possibility of forming a dead zone must be considered. When a dead zone forms, the friction factor (m) becomes $m = 1$, and the data should not be considered in determining friction values.

6.2.2 Central Bursts

Central bursting (or chevroning, or cupping) is a serious

defect in wire drawing and extrusion. As shown schematically in Fig. 6.2, and photographically in Fig. 6.10, this defect is characterized by the periodic repetition of a central fracture. An internal defect of this type is particularly troublesome in practice because it may cause failure in service, while the product's exterior does not reveal its presence.

Central bursting occurs within a unique range of reduction, die cone angle, friction, and prior strain hardening. In Ref. 27 an attempt has been made to quantitatively define this area. The sound flow velocity field of Fig. 6.5 is inadequate to analyze the occurrence of central bursting, and another velocity field has been postulated in Ref. 27. The predominance of the defective flow velocity field over the sound flow of Fig. 6.5, is held to depend on which field requires the least amount of energy for the actual process considered. Through application of the upper bound approach to this new velocity field, a criterion for central bursts has been developed. The mathematical derivations are given in Ref. 27.

Fig. 6.11 presents the central burst criterion (solid lines) for several values of the friction factor (m) plotted as functions of percent reduction and semi-cone angle. In Fig. 6.11, each solid line of constant friction factor (m) forms a boundary above which central bursts will definitely not occur and below which central bursts may occur. More work must be done to define, accurately, the role of strain-hardening, but the present analysis, at least, gives the die designer a safe zone for the avoidance of central bursts.

6.2.3 Clarification of Terms

Primary Metal Forming - Those processes which form rods, strips, plates and sheets. These may be finished products themselves but generally are used as material inputs to other or secondary metal forming processes.

Secondary Metal Forming - Those processes which form a

finished product or component. These processes may produce forms which are used as material inputs to subsequent processes, but in general produce the finished component.

Previously Consumed Energy - This is the total energy required to form a material up to but not including secondary metal forming. That is, the energy to mine, extract, refine and primary metal form a material. For a complete explanation, see Energy-Systems View - Energy Considerations in Metalforming - Cold Extrusion vs. Hot Forging & Machining, Sec. 4.0.

Central Burst - This is the name given to certain processing defects present in drawn and extruded products. They are chevron shaped in cross section but are actually conical voids within the material. These internal defects are impossible to detect without costly and time consuming inspection procedures.

It is shown in this case study that the elimination of processing defects can result in substantial savings in energy. The major portion of energy saving comes from a reduction in "previously consumed energy" that results from the reduction in the scrap associated with the former process. This energy is defined as the sum of the energy requirements from all the processes necessary to transform raw material into a process input. "Previously consumed energy" is all the energy for mining, extraction, refining and primary metal forming. This energy does not include the secondary metal forming energy.

Central burst defects were removed from industrial processing only after concentrated research and analysis. Other processing defects, such as "fur-tree" or "fishskin" in tube and tubular products, may also be eliminated through research and analysis; thereby effecting an energy and cost savings.

6.3 Analysis of Energy Savings by Elimination of Central burst defects

The case of central burst defects in automobile steering linkage is used to demonstrate the amount of energy savings available by the

elimination of processing defects. The energy savings are based on "previously consumed energy" only. The actual extruding process energy need not be calculated. A secondary energy savings may be said to occur, if the products do not require 100% inspection. The energy and cost of such testing as ultrasonic and X-ray are no longer required. The energy savings associated with the inspection methods are not as substantial as those associated with "previously consumed energy", however.

The dimensions of the steering linkage are shown in Fig. 6.12. The material volume is calculated to be 465.6 cm^3 . The linkage produced from cropped steel rod has a calculated weight of 3.67 kg by:

$$465.6 \text{ cm}^3 \cdot (\text{Density of Steel} = .0079 \frac{\text{kg}}{\text{cm}^3}) = 3.67 \text{ kg}$$

or 8.1 lbs.

Approximately 14 million steel steering linkages are produced in the United States for cars, buses, trucks and farm equipment each year. Of these, 10% were produced with central burst defects during those years before the defect could be prevented. If a more conservative estimate of 3% defective linkages, due to central burst defects, is used, a total of 420,000 defective linkages were produced per year. A total volume of $6.51 \times 10^9 \text{ cm}^3$ or $1.12 \times 10^8 \text{ lbs.}$ ($5.6 \times 10^4 \text{ Tons}$) of steel was scrapped because of central burst defects. Although this material reentered the metal forming industry as salvaged scrap metal, a large amount of energy had already been expended and wasted. This energy - the "previously consumed energy" - was used to produce the rods which were the raw material input to the extrusion process producing the steering linkage. The "previously consumed energy" can be calculated in the following manner: The energy required to produce steel rods, strips, sheets and plates, is approximately:

$$29 \text{ million BTU's per ton, or } 2.71 \times 10^6 \frac{\text{kg-cm}}{\text{cm}^3}$$

Therefore, the "previously consumed energy" of one defective linkage

is:

$$\begin{aligned} & (\text{the required energy}) \times (\text{volume of each shaft}) = \\ & \quad \text{"previously consumed energy" or} \\ & (465.6 \text{ cm}^3) (2.71 \times 10^6 \frac{\text{kg-cm}}{\text{cm}^3}) = 1.26 \times 10^9 \text{ kg-cm/per linkage} \end{aligned}$$

Considering 420,000 linkages defective per year, the total "previously consumed energy" is:

$$4.2 \times 10^5 \text{ linkages} \cdot 1.26 \times 10^9 \frac{\text{kg-cm}}{\text{linkage}} = 5.29 \times 10^{14} \text{ kg-cm}$$

or

$$4.2 \times 10^5 \text{ linkages} \cdot \frac{8 \text{ lbs.}}{\text{linkage}} \cdot 1.45 \times 10^4 \frac{\text{BTU}}{\text{lb.}} = 4.87 \times 10^{10} \text{ BTU's}$$

These figures represent the amount of energy lost through material defects. The cost of this lost energy can be approximated.

The energy cost to produce a ton of steel is about \$ 70.00 in 1979. As a result of central burst defects, \$ 117,600 of energy cost would have been incurred without producing a sound product. The reader is reminded that these figures do not include the actual secondary metal forming energy required by the extrusion process.

The elimination of processing defects has been shown to effect both a savings in energy and a removal of processing restrictions from the metal forming industry at large. The prevention of processing defects resulted from a dedicated effort by both researchers and industry. Trial and error methods and non-analytical approaches produced only local or temporary solutions to the metal forming defect problem.

There are many processing defects plaguing the metal forming industry which still need to be studied and analyzed. One such defect is the fur-tree or fishskin defect. This defect manifests itself during the extrusion of tubes and tubular products. There are today a few promising theories which may lead to the elimination of this defect from the extrusion process. However, in order to accomplish this, the defect and the process of tube extrusion must be fully and carefully analyzed.

The elimination of the fur-tree defect in tube extrusion will also lead to an energy savings by the reduction of material waste, thereby conserving the "previously consumed energy" in a manner similar to that demonstrated by the case of central burst defects.

The task of removing the restrictions that processing defects place on the metal forming industry is enormous. The same precise and analytical manner of defect investigation used by Harris, Remmers, Jennison and Avitzur should be continued if industry-wide results are to be obtained.

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FIG.6.1 CRITERION TO PREVENT CENTRAL BURST IN MATERIALS THAT STRAIN HARDEN.

FIG.6.2 EFFECT OF DIE GEOMETRY ON THE OCCURRENCE OF CENTRAL BURSTING .

FIG.6.3 THE DIE AND WIRE IN WIRE DRAWING AND EXTRUSION.

FIG.6.4 SCHEMATIC ILLUSTRATION OF THE EFFECT OF TOOL ANGLE AND MODE OF FLOW INCLUDING CENTRAL BURST ON DRAWING FORCE.

FIG.6.5 VELOCITY FIELD.

FIG.6.6 COMPARISON OF EXPERIMENTAL WITH THEORETICAL CURVES FOR GRID LINE DISTORTION

FIG.6.7 PORTIONS OF THE DRAWING STRESS TO OVERCOME RESISTANCE.

FIG.6.8 THE EFFECT OF α AND REDUCTION ON THE RELATIVE DRAWING STRESS

FIG.6.9 DRAW STRESS VS. CONE ANGLE AND REDUCTION.

→
DIRECTION OF FLOW

FIG.6.10 CENTRAL BURST DEFECT.

FIG.6.11 CRITERION FOR CENTRAL BURST

FIG.6.12 STEERING LINKAGE.

7.0 PRECISION FLASHLESS CLOSED DIES FORGING

Michigan Screw was visited and preliminary information was gathered. They have offered their cooperation but asked to postpone the preparation of a case study until they have fully protected their proprietary interest in the process. Hence, it appears that the "Precision Flashless Closed Dies Forging Process" can become a case study in the second year of the project.

Conventional closed dies forging is performed hot and about 25-30 per cent of the material entering the press ends up as scrap, mostly in the form of discarded flash. (See Fig. 7.1)

A new concept called "Precision Flashless Closed Dies Forging" is now starting to emerge. This process eliminates the flash and reduces the amount of scrap to zero. Savings of 30 per cent of the material with an energy content of 29,000,000 BTU/TON may amount to a substantial energy savings even if only a small per cent of the present day conventional hot forging with flash is replaced by flashless forging.

Figure 7.2 shows a typical component currently forged with a flash, which can be converted to flashless forging. In Germany and Japan where flashless forging is more advanced than in the United States, the Maypress which is produced by Kamatsu of Japan was found to be the most suitable for flashless forging because the process requires a strong yet highly flexible press. In Japan and Germany many suitable components are already being manufactured by flashless forging with tremendous cost reductions through material and energy savings.

In the United States, several companies, including Chrysler, are now convinced of the emergence of this process. Moreover, the Michigan Screw Company has started producing automotive parts by this new process. Our familiarity with the company effort dates back to an initial review of the process. Prof. Avitzur was serving as a consultant to Michigan Screw on the economic feasibility of the process.

FIG. 7.1 SCHEMATIC OF FORGING OF A FLAT COMPONENT WITH FLASH.

NOTE.

ARROWS INDICATE
DIRECTION OF FLOW

FIG. 7.2 FORGING WITH A CONTOURED FLASH LINE.

FIG. 7.3 SCHEMATIC OF PRESS AND PRESS FORCE CHARACTERISTICS

8.0 CONTINUOUS HYDROSTATIC EXTRUSION

VERSUS CONVENTIONAL WIRE DRAWING

8.1 An Historical Perspective of Wire Drawing:

Today modern man is increasing his need and demand for wire products. Wire, once utilized only for its mechanical strength, is now exploited for its conductive characteristics. From the flow of thousands of kilowatts of power, to the connection of microamps used in communication, switching and computing devices, wire is the artery material of modern civilization.

The production of wire has been dominated, until recently, by one method, that method commonly known as wire drawing. The origins of wire drawing lie in antiquity. The consistency of workmanship of some wire artifacts from ancient Egypt leads some researchers to believe they had a working knowledge of wire drawing.^[1] The lack of archaeological evidence - the actual discovery of an Egyptian draw plate or draw die - overshadows this theory. E. G. Thomsen and H. H. Thomsen proposed that the drawplates and dies used in antiquity may have been made from scarce or precious materials.^[1] It would be logical to assume, therefore, that once the drawplate or die became non-functional, it was melted for reuse.

Wire making as an important industry is believed to date from at least 800 A. D.^[2] Although Theophilus described the process in detail in his Latin work of about 1100 A. D., there has been no date established as to when wire drawing became the dominant method for the production of wire.

Over the centuries improvements in the wire drawing process have been made. The modern wire drawing operation employs a multi-station machine with one die or reduction in cross-sectional area effected at each station. The drawing force is supplied by electric powered bull-

blocks. Sensing devices monitor the tension of the wire between stations.

In recent years there have been several new concepts proposed for the production of wire. These new methods are now starting, on an experimental basis, to challenge the dominance of wire drawing as the major method of wire production.

During the years of practice and study, the process of wire drawing has been refined and perfected. Usually, in a typical medium size wire product, the price of the raw material comprises the bulk of the cost, while expenditures on reducing the diameter by drawing may be less than six percent of the total cost.

To justify the transition, any new process that is destined to replace the well-established wire drawing process must exhibit very high potential savings. An analogous situation in a more commonly recognized technology would be offering of a new motor (electric) to replace the reciprocal internal combustion engine in modern automobiles. Invested capital, inertia, familiarity and resistance to change have to be pushed aside before a transition can be made.

8.2 Overview of Western Electric Developmental Effort:

Today there exist a few experimental processes which may someday compete with conventional wire drawing as the major process for the production of wire. These new methods are Continuous Extrusion Forming, better known as Conforming, Combined Hydrostatic Extrusion and Drawing, Shaving and Helical Extrusion, Extrolling and Continuous Hydrostatic Extrusion.

The subject of this case study is the comparison of Continuous Hydrostatic Extrusion by the Fuchs' Method to conventional wire drawing in the production of copper wire. It will be shown that a wire extrusion process made continuous is economically competitive with conventional wire drawing based on energy considerations. Although the energy needed for the deformation of the raw material is almost the

same for each process, (Fuchs' - and conventional wire drawing) the Fuchs' Method produces the wire in a single pass by taking a single large reduction in cross-sectional area. The major energy savings in the Fuchs' system, therefore, is the elimination of the intermediate anneals necessary for large reductions in area which are needed by conventional wire drawing. There are other energy saving features which will be discussed later in the text.

The continuous hydrostatic extruder was developed at a Western Electric research facility. The Engineering Research Center (ERC) is a research and development and prototype development facility of Western Electric, and is concerned with improvements in manufacturing processes. Located at Princeton, New Jersey, ERC employs several hundred scientists and engineers that work closely with WE's Product Engineering Control Center (PECC). PECC has a corporate responsibility for further proving of new manufacturing technologies and the phasing into production of those ideas that have demonstrated "production line" feasibility and an economic attractiveness. PECC is part of the Atlanta facility and has access to a miniature plant at which it can do simulated production runs.

The principal impetus for the development of Continuous Hydrostatic Extrusion came from Mr. Frank Fuchs, a mechanical engineer who has spent over thirty years with Western Electric and is the inventor of more than 75 patents issued to the Company. Hydrostatic extrusion was a developmental idea that was worked on by the cable and wire industry as early as 1955; however, the early work was commercially unworkable because the approach taken was a "batch process", and any commercial wire-making method had to be continuous and be capable of running at a high speed. Research on high pressure hydrostatic continuous wire extrusion began in earnest at the ERC under Fuchs in the mid 1960's, and workable results were reported in 1970 using pressurized fluid. The latest machine prototype uses a system that develops the tremendous pressure of up to 500,000 psi for extrusion by an ingenious

design of a continuously forward moving chamber and which is made of assembled solid segments. In the first design the continuous forward motion was provided through highly viscous media (heated beeswax) while in the present design the extrusion force is provided by a segmented chamber in contact with the billet.

8.3 Basic Concepts Related to the Fuchs' Method:

One metal forming process is classified as the "flow through" process, schematically shown in Fig. 8.1.^[3] In Fig. 8.1, a die with a central opening separates the raw material from the product. When the pressure on the entrance side of the die is sufficiently higher than the pressure on the exit side, the metal is forced to flow from the higher pressure chamber to the lower pressure chamber. The product is usually a straight rod of a final cross-section shaped as the opening of the die. The opening of the die may have a variety of shapes. Several openings in the die may serve for the production of several products from a single stock. The die opening may also be of tubular shape for the production of hollow tubes.

Two well-established conventional flow through processes are extrusion and wire drawing.^[3] For both processes the stock is a cylindrical rod that is reduced to a smaller cross sectional product while passing through the die. For extrusion the stock, confined in a chamber, is pushed through the die by a ram. In wire drawing the stock material is pulled through the die by tension produced on the wire product. A shortcoming of the wire drawing process is a limit on the pulling force. This force cannot be greater than the flow strength of the material or fracture will occur. This limitation then dictates that only small reductions in cross-sectional area can be effected in a single pass through the die. If unexhausting stock is supplied the process becomes continuous. Larger reductions are attained by numerous successive passes through the dies, with each pass producing a small reduction. Because of strain hardening of the material, it may be necessary to anneal the product between passes

through the dies. This annealing is eliminated in extrusion and constitutes the major energy savings. By using the process of extrusion, large reductions can be attained in a single pass but in most extrusion processes only finite lengths can be extruded and the process is an interrupted one.

In Fig. 8.2, the relative positions of the chamber, die, ram, raw material and the product during extrusion are portrayed. During the process of direct extrusion, the die and the chamber are solidly clamped together. The ram is pushed into the chamber to produce pressure on the stock high enough to force it to flow through the die. During the process of indirect extrusion (Fig. 8.3), the ram and the chamber are clamped rigidly together, and the die is pushed into the raw material to produce the necessary pressure to force the stock to flow through the opening in the die.

A look at the relative motion between the chamber and the raw material shows that during direct extrusion, the workpiece moving toward the die encounters friction resistance along the wall of the chamber, as shown on the top half of the chamber. This friction has to be overcome by the ram force. Thus, the ram pressure, while being transmitted from the ram to the die side through the raw material, is reduced. The pressure profile is graphically displayed on Fig. 8.4. For direct extrusion, the pressure profile, as shown, indicates that some ram pressure is wasted and never reaches the die side where it is needed. Billet length is thus limited due to excess ram pressure. During the process of indirect extrusion, no relative motion between the chamber and the workpiece is observed (ignoring the dead-metal zone) and the profile of the pressure becomes more uniform.

A different design concept, forwarded long ago by Robertson, can now be introduced.^[3] Let the ram, chamber, and die be motivated separately. If the die is set stationary, then the ram and chamber move toward the die at speeds V_r and V_c respectively. A logical development for this design follows. If the chamber moves faster than

the ram, then the friction from the chamber will act on the workpiece. When V_c is greater than V_r , the pressure profile demonstrates a higher pressure at the side of the die. The longer the chamber is, or the larger the speed difference between the chamber and the ram, the lower the ram pressure will be. At the limit the situation of zero ram pressure may exist.^[3] The workpiece may move faster than the ram and separate from it. The ram becomes redundant and may be dispensed with.

When a ram is not in use, the original diameter of the workpiece should be large enough to fit snugly into the chamber. At the entrance, the contact between the workpiece and the chamber generates only a slight "friction-caused pushing" force due to the forward moving chamber.

This push causes ever so slight an upsetting of the billet ahead because billet movement forward is slower. This slight upset results in a strong force pushing forward, a large upset and enhancement of the pressure. This reaction increases, with enough pressure developed at the die to cause extrusion.

For all flow through processes, the pressure differential at the die exit can be approximated by:^[3]

$$\frac{P_1 - P_2}{\sigma_o} = \ln \left(\frac{A_o}{A_f} \right) \quad \text{Eq. (8.1)}$$

where: σ_o is the flow strength of the material at the operating temperatures.

P_1 is the pressure on the raw material side of the die.

P_2 is the pressure on the exit (product) side of the die.

A_o, A_f are the original and the final cross-section areas of the raw material and the product respectively.

Because of redundant deformations and friction losses which are not accounted for by the above expression, the actual pressure differential must be higher.^[3]

As the need for the ram becomes obsolete, the possibility of an open chamber extrusion becomes more of a reality and less of a dream. In recent years, several new concepts for the production of wire have been proposed and developed and which strive for a continuous process with large reductions per pass.

A description of developments in wiremaking machines, concepts and methods is detailed in Appendix A, "Recent Developments of Continuous Wiremaking Machines" by B. Avitzur. The new concepts dealt with are:

1. 'Continuous Extrusion with Viscous Drag' by Fuchs.^[4]
2. 'Continuous Chamber Extrusion' by Fuchs.^[5]
3. 'Continuous Extrusion Forming' (Conforming) by Green^[6] and the Linex Process
4. 'Combined Extrusion Drawing' for (a) Fine Wire,^[7] and (b) Heavier Gauge.^[8,9,10]
5. 'Helical Extrusion' by Green.^[11,12]
6. 'Shaving' by Shaw and Hoshi,^[13] and
7. 'Extrolling' by Avitzur.^[14,15,16,17]
8. 'The Melt-Extraction Process'.^[18,19]

Processes listed 4(a) and 5 above are not truly steady-state continuous processes, but are included because the uninterrupted portion of the cycle which in each case is excessively large. Each process will be described briefly in Appendix A, its concept explained, and some of its shortcomings, if any, pointed out.

In this report, a case study of Continuous Hydrostatic Extrusion by the Fuchs' Method, a comparison of this new method of copper wire

production with the traditional method of wire drawing, was conducted on an energy basis. There were several considerations for performing this comparison as part of the study of energy conservation in metal forming. The first being the existence of a fully operational, experimental, continuous hydrostatic extruding machine. The machine, designed by F. Fuchs,^[7] produces wire by a continuous method with a single large reduction pass. Visits to the research facility, and meetings with Mr. Fuchs, provided insight into the concept and operation of the continuous hydrostatic extrusion machine.

A second consideration was that both processes - continuous hydrostatic extrusion and conventional wire drawing - employ a conical converging die. Metal flow through conical converging dies has been analyzed in great detail;^[20,21] therefore, a comparison of continuous hydrostatic extrusion to conventional wire, on an energy basis, is a straight forward task of applying the analysis of metal flow through conical converging dies to both processes under similar processing parameters. These parameters are:

1. The type of wire produced, that is, the same raw material would be used in both processes.
2. The amount of reduction in cross-sectional area produced.
3. The friction factors.
4. The semi-cone angle of the die.
5. The land length of the die.
6. The machine efficiencies.

Under these conditions, it is possible to calculate the total energy both processes would require to produce wire.

Western Electric's interest in this metal forming concept is quite obvious. Considered to be the largest domestic user of copper, the Western Electric Company is wholly owned by the American Telephone and Telegraph Company (AT&T), and is the primary supplier of telecommunicat-

ions products to the operating companies of the Bell System. After facing severe declines in sales in 1975 and 1976, Western Electric experienced a turn-around in 1977, and in 1978 had reported revenues of \$9.1 billion and profits of \$561 million. Western Electric operates 20 major plants, employs 155,000 people, or one-sixth of the Bell System work force, and its Atlanta plant is the world's largest cable plant with 1.8 million square feet, and a 1978 production level of 115 billion conductor feet. Together with Bell Labs, Western Electric is responsible for lowering manufacturing costs and improving product performance capabilities for the operating companies and their customers.

8.4 Description of the Fuchs' Continuous Hydrostatic Extruder and Extruding Process:

A plant system for conventional wire drawing is schematically shown on Fig. 8.5A.^[22] This system is similar to an existing wire drawing facility of the Western Electric Corporation in Atlanta, Ga. An alternative system, one using continuous hydrostatic extrusion for the wire production, is shown on Fig. 8.5B.

The conventional wire drawing system consists of a primary wire draw (No. 1 wire draw) which supplies material for the secondary wire draw. Two parallel secondary wire drawing systems are shown. After the primary draw, a choice of the type of wire insulation is made. This choice dictates which secondary branch is used. One branch is designed to place a (P.I.C.) insulator on the wire and the other a pulp insulator. Following the secondary wire draw in the conventional system, the material is annealed. For P.I.C. insulation, a preheat operation, before application of the insulator and a cooling operation after, is required.

In comparison to the conventional system, the continuous hydrostatic extrusion plant system produces the wire in a single operation.

This system also eliminates the wire anneal necessary in the conventional wire drawing system.

It should be noted that both the conventional wire drawing systems and the continuous hydrostatic extrusion systems are identical from the preheat operation onward to finished product when P.I.C. insulation is used, and from the take up operation when the pulp insulation is used.

The continuous hydrostatic extrusion plant system offers a system which; (1) has fewer process operations than the conventional wire drawing system, and (2) offers the elimination of costly wire annealing.

The Continuous Hydrostatic Extruder was designed to use a .3125 inch (.793 cm) diameter wire rod at room temperature as the raw material input.^[23] The wire rod is placed into the extruder by hand during the machine start up. When the extruder is in full operation, it provides the pulling force for feeding the stock off the feed coil. The wire rod passes through a straightening jig before entering a coating head. The coating head places a viscous medium on the wire rod, approximately .001 to .002 inches (.0025 to .005 cm) thick.^[23] The viscous medium, usually low density polyethylene or beeswax, increases the apparent rod diameter. This fact is used to produce a hydrostatic pressure on the input rod which allows hydrostatic extrusion to be achieved.

The main component of the extruder system is the endless, traveling block extrusion chamber. The chamber is formed by circumferentially quartered segments, Fig. 8.6. Each segment is 2.25 inches (5.71 cm) in length. The chamber segments, as seen in Fig. 8.6, are basically triangular and have a 20° Fellows stub gear machined into two of the corners.^[23] These gears provide a means to drive the segments through the extruder.

During the segments internal 'forward pass' through the extruder, approximately 1/2 of the total number of segments form a 24 inches

(60.96 cm) long pressure chamber. The remaining segments are either on the 'return pass' or at the entrance 'convergence', or exit 'divergence' portion, of the extruder. The segment travel path and the main body of the extruder are shown schematically in Fig. 8.7.

The chamber segments converge upon the feedstock, at the entrance of the machine. As the chamber segments move forward toward the extrusion die, they also carry the feedstock which is coupled to them by the viscous medium. The forward moving segments pass over the extrusion die. A pressure profile as shown in Fig. 8.8 is developed. The pressure developed at the entrance side of the extrusion die is great enough to cause the wire rod to be extruded. After passing over the extrusion die, the segments exit the machine, are split into their respective quadrants, and return to the feedstock entrance via the external return path. The segments close again on the coated wire rod feedstock, and the process is repeated.

The chamber segments are driven through pinion gears. These gears, in turn, are driven by a planetary gear reducer powered by a hydraulic motor. The pinion gear meshes with one stub gear rack from two different segments. Therefore, four circumferentially arranged segments which make up a pressure chamber of one segment length, are locked together and are driven by four pinion gears. The extruder has 16 driving pinion gears, each independently powered by a hydraulic motor through a gear reducer.

The chamber segments must be held together axially and radially to prevent fluid medium leakage and feedstock flashing. The axial force to accomplish this is provided by four pinion gears, coupled to hydraulic motors, set just ahead of the extrusion die. In this case, the segments drive the pinion gears but this motion is retarded by the hydraulic motors. Therefore, these gears and hydraulic motors act as brakes applying an axial load to the segments.

A radial force is transmitted to the segments by hydrostatic bearings acting on the flat back side of each segment. (See Fig. 8.6). The

fluid in the pressure pad is separated from the segments by a continuous, hard-coated, stainless steel belt. This prevents the pressure pad fluid from leaking between the segments. The belts are driven through the machine by the contact friction between themselves and the chamber segments. The pressure pad fluid medium is grease which is pumped into the machine by a two-piston continuous intensifier. There is some heat generated here by the pressure pad-belt friction as the segments move through the machine. This excess heat is removed by cooling water flowing at approximately 6 gals./min. through cooling passages machined into beryllium-copper shoes and which also contain the fluid pressure zones. This radial pressure, along with the axial force need only be supplied to the segments during the 'internal forward pass'.

The extrusion die is positioned and held axially by a die stem. The die stem is attached to a load cell at the product exit end of the extruder to measure the extrusion loads. The extrusion die has a tight fit within the chamber bore, preventing the die from swelling.

The die stem bore is heated to prevent the hydrostatic medium from solidifying within it. The solidification of the medium could cause a back pressure high enough to break the die stem or stop the extrusion. The heating is accomplished by electrical resistance heating element in the bore of the stem.

8.5 Operational Analysis of the Continuous Hydrostatic Extruder:

During early experiments with the extruder, the force needed to move the chamber segments forward, the axial force produced by the braking motors, and the pressure in the three pressure zones were recorded. This monitoring was done during the production of aluminum wire of a final diameter of .015 inches (.0381 cm), a reduction in area of 400 to 1. The extruder was viewed as an open steady-flow thermodynamic system. The work and heat inputs, outputs, and losses were calculated. The efficiency of the extruder was established by dividing the sum of the

work of forming and the braking motor output by the drive motor inputs. This was done for the aluminum wire production with a calculated efficiency of 52%.^[23]

Copper wire of a final diameter of .025 inches (.0635 cm) was also produced by the extruder, effecting a 150 to 1 reduction in area. The efficiency analysis was not done for the copper wire production; therefore, for this case study, the extruder efficiency will be assumed to be 50%. It will be shown later that the machine efficiency and the process energy savings are a minor component of the overall energy savings.

The extruder has operated experimentally at chamber pressures in excess of $2.01 \times 10^4 \text{ kg/cm}^2$ ($2.86 \times 10^5 \text{ psi}$), and input rod speeds of 14.93 m/min. (49 ft/min). The product speed reached 3657 m/min. ($\approx 12,000 \text{ ft/min}$). It can be as high as 6096 m/min. (20,000 ft/min. or 227 miles/hr.). These high exit speeds may be reduced by using an extrusion die with 4 to 6 openings, i.e., producing 4 to 6 wires from one input rod. This not only reduces the exit speed but reduces the actual extrusion force, thereby increasing the energy savings of the machine.

8.6 Units, Conversions and Conversion Factors:

This section is added as a convenience to the reader and measurement units used in this case study are:

Pressure (P)	kg/cm^2
Flow Strength (σ_o)	kg/cm^2
Energy	kg*cm/cm^3
Heat Capacity (Cp)	$\text{kg*cm/cm}^3/^{\circ}\text{C}$
Material flow	m/min

Normally the specific heat of a material can be found in convenient tables with the prevailing units of cal./g./ $^{\circ}\text{C}$. A conversion

factor for this case study was established. For example, the specific heat of Electrolytic Tough-Pitch Copper, at 20°C, is 0.092 kcal./kg/°C. To translate this value into kg*cm/cm³/°C, the following conversion factor has been established:

$$1 \text{ (kcal.)} = 4.27 \times 10^4 \text{ (kg*cm)}$$

$$1 \text{ cm}^3 = 8.9 \text{ gm or } .0089 \text{ kg of copper}$$

$$1 \text{ (kcal./kg/°C)} = \frac{4.27 \times 10^4 \text{ (kg*cm/kg/°C)}}{.0089 \text{ (kg/cm}^3\text{)}}$$

Therefore:

$$1 \text{ (kcal./kg/°C)} = 3.79 \times 10^2 \text{ (kg*cm/cm}^3\text{/°C)}$$

The specific heat of copper is 0.092 (kcal./kg/°C).

This converts to:

$$0.092 \text{ (kcal./kg/°C)} \cdot 3.79 \times 10^2 = 34.92 \text{ (kg*cm/cm}^3\text{/°C)}$$

Another conversion is needed for the units of energy specifically from kw-hr to kg*cm. Related on a volume basis it then becomes kw-hr/lb to kg*cm/cm³.

$$1 \text{ kw-hr} = 3.671 \times 10^7 \text{ kg*cm}$$

For copper:

$$1 \text{ cm}^3 = 8.9 \text{ gm}$$

$$8.9 \text{ gm}/(453.6 \text{ gm/lb}) = .0196 \text{ lb}$$

$$1 \text{ lb} = 1/.0196 = 50.96 \text{ cm}^3$$

$$1 \frac{\text{kw-hr}}{\text{lb}} = 3.671 \times 10^7 \frac{\text{kg*cm}}{\text{lb}} \times .0196 \frac{\text{lb}}{\text{cm}^3}$$

$$1 \frac{\text{kw-hr}}{\text{lb}} = 7.26 \times 10^5 \frac{\text{kg*cm}}{\text{cm}^3}$$

Conversion Factors

To Convert From	To	Multiply By
psi	kg/cm ²	7.031×10^{-2}
kcal./kg-°C	kg*cm/cm ³ /°C	3.79×10^2
kw-hr/lb	kg*cm/cm ³	7.26×10^5
Ft/min	m/min	3.048×10^{-1}

8.7 Adiabatic versus Isothermal Processing:

In this case study, conventional wire drawing is assumed to be an isothermal process. In wire drawing, the wire product heats somewhat but the reduction, and, therefore, the temperature rise at each station is limited. The wire also has the opportunity of cooling in its travel between stations. Therefore, the assumption of isothermal behavior is tolerated.

During wire extrusion on the other hand, very large reductions cause some of the work of internal deformation, redundant power and friction losses to be converted into heat. Therefore, an assumption of adiabatic behavior is more realistic when considering continuous hydrostatic extrusion.

The analysis of metal flow through conical converging dies as isothermal and adiabatic processes has been conducted by Dr. B. Avitzur, Lehigh University.^[20,21] In this analysis, the flow strength of the material is given as a function of the temperature, effective strain and effective strain rate. An upper-bound approach was used to compute the temperature rise along the path of flow at small but finite increments.

In general, it can be shown that the energy absorbed by wire in deformation per unit volume can be approximated by:

$$W = \ln \left(\frac{A_o}{A_f} \right) \quad \text{Eq. (8.2)}$$

Therefore, for adiabatic processes, the temperature rise would be: [3]

$$\Delta T = \ln \frac{A_o/A_f}{C_p} \quad \text{Eq. (8.3)}$$

Once the temperature rise, the effective strain and effective strain rate are known, the flow strength can be calculated. This can then be related to the energy needed to produce a wire with set parameters of:

- 1) radius ratio
- 2) semi-cone angle of the die
- 3) the friction between the die and input rod
- 4) material characteristics such as:
 - a) melting temperature
 - b) recrystallization temperature
 - c) tensile strength
 - d) yield strength
- 5) starting temperature
- 6) speed of processing

The above analysis has been incorporated into a computer program available at the Institute of Metal Forming, Lehigh University, Bethlehem, Pennsylvania. This program was used to calculate and compare the energy needed to produce copper wire by both isothermal and adiabatic processes. The results are shown in the back portion of this case study in Exhibit 8.1 and Fig. 8.9. The computer program shows pressure as kg/cm^2 , and by multiplying by (cm/cm) the energy units kg-cm/cm^3 can be obtained.

In Mr. Fuchs' experiments in producing wire by continuous hydrostatic extrusion, OFHC copper was used as an input rod material. [24]

OFHC copper has the following characteristics:

Melting temperature	1083°C
Recrystallization temperature	850°C
Tensile strength	2518 kg/cm^2
Yield strength	857 kg/cm^2

Therefore, the strength equation

$$\sigma_o = \left\{ \left(1 - \frac{T}{1083} \right) \left(857 + 18.45 \tan^{-1} \theta \right) \right\} \quad \text{Eq. (8.4)}$$

is utilized. (T) is the instantaneous temperature of the material, and (θ) is the effective strain (in degrees). It will be noted that at zero degrees centigrade, the flow strength will be 857 kg/cm^2 , and at the highest strain ($\theta \rightarrow \infty$), ($\arctan \theta \rightarrow 90^\circ$) the strength will not exceed 2518 kg/cm^2 . The specific heat of OFHC copper at 20°C was taken to be $34.91 \text{ kg*cm/cm}^3/^\circ\text{C}$ for the adiabatic case, and $1.0 \times 10^6 \text{ kg*cm/cm}^3/^\circ\text{C}$ for the isothermal case.

8.8 Analysis of Processes:

The energy considerations in comparing Continuous Hydrostatic Extrusion to conventional wire drawing will be as follows:

- 1) Total Energy (Ideal energy) for the wire production.
This includes the work of deformation, redundant power and frictional losses as described in the previous Section (Adiabatic vs. Isothermal Processing).
- 2) Total Energy (Non-Ideal). This will be energy needed for the wire production including machine efficiencies and the effect of multiple wire production on energy needed.
- 3) Annealing energy. This will include various numbers of intermediate anneals for conventional wire drawing. It will also include annealing furnace efficiencies.

Some attention will be drawn to a physical comparison between machinery needed to perform the processing. These comparisons will focus on the energy needed to house, light and heat the area surrounding the machines.

In his experiments, Mr. Fuchs produced 22 gage OFHC copper wire. The input rod to the continuous hydrostatic extruder is .3125 inches

(.793 cm). This, therefore, is a reduction in area of 99.3%.

The computer program for Adiabatic and Isothermal Process Energy gave the following results for 99.3%, reduction in area:

- 1) The continuous hydrostatic extruder (an adiabatic process) would use $8,592.0 \text{ kg}\cdot\text{cm}/\text{cm}^3$ of energy to produce 22 gage wire out of .3125" rod.
- 2) Conventional wire drawing would use $10,494.3 \text{ kg}\cdot\text{cm}/\text{cm}^3$ of energy to produce the same wire.

This results in an energy savings of 18.1%.

In the Section "Operational Analysis of the Continuous Hydrostatic Extruder," it was stated that the extruder has an efficiency of approximately 50%. A common figure for the efficiency of most conventional wire drawing machines is 23%. These assumptions increase the total energy for each process to $17,184.1 \text{ kg}\cdot\text{cm}/\text{cm}^3$, and $45,627.6 \text{ kg}\cdot\text{cm}/\text{cm}^3$ for the extrusion and the wire drawing process respectively. The percent energy savings of Continuous Hydrostatic Extrusion by the Fuchs' Method over conventional wire drawing then increases to 62.3%.

If a multiple hole die was used in the extrusion process, a four hole die for example, the exit speed would be reduced but the volume flow rate of the material through the machine would remain unchanged. A more significant change is the reduction of the actual process energy.

The reduction in the actual processing energy comes about in the following manner. As stated previously, the percent reduction in cross-sectional area, for 22 gage wire in question, is 99.3%. This means the final wire product has a cross-sectional area of $.00127 \text{ cm}^2$ ($.0005 \text{ in}^2$). If a four hole die is used producing four 22 gage wires, the sum of their cross-sectional areas is $.005 \text{ cm}^2$ ($.002 \text{ in}^2$). This equivalent final product area is only a 97.3% reduction from the original area. A decrease in the percent reduction in cross-sectional area in extrusion or wire drawing effects a decrease in the process energy. This can be seen from Eq. (3.2) of Sec. 3.1, the equation for calculating the ex-

trusion force. The cross-sectional areas of the input and output material are related by the natural log of the ratio of their radii, $\ln(R_o/R_f)$. If the original radius remains unchanged at $.793 \text{ cm}^2$, and the final radius increases, in this case a calculated equivalent radius, based on the increase in final area, the extrusion force will decrease, which can be seen by studying Eq. (3.2).

When a four hole extrusion die is used, the process energy is $6,174.0 \text{ kg*cm/cm}^3$. Taking the machine efficiency of 50% into account, the figure becomes $12,348.1 \text{ kg*cm/cm}^3$. Compared to producing one wire by continuous hydrostatic extrusion, this is, in itself, a 28% savings in energy. Compared to conventional wire drawing, it is a 72.9% savings in processing energy for 22 gage wire. These figures are tabulated in Exhibit 8.2 for the reader's convenience.

We will consider next the energy needed for intermediate anneals. The continuous hydrostatic extruded wire would not require any intermediate anneals. The conventional wire drawn wire might require several. In making a comparison between the two processes, the energy for one intermediate anneal will be calculated.

A first order approximation of the ideal anneal energy for a single intermediate anneal can be obtained from the specific heat of the material and the change in temperature. The copper wire in question is annealed at 482°C (900°F).^[25] Therefore, the ideal anneal energy is:

$$\begin{aligned} W_{Ai} &= C_p \text{ copper } \Delta T \\ \Delta T &= 482^\circ\text{C} - 20^\circ\text{C} = 462^\circ\text{C} \\ C_p &= 34.91 \\ W_{Ai} &= (34.91) \cdot (462) = 16,126.158 \frac{\text{kg*cm}}{\text{cm}^3} \end{aligned}$$

This ideal anneal energy value is affected by the efficiency of the annealing furnace. At 100% furnace efficiency, the actual anneal energy for one intermediate anneal, would equal the ideal anneal energy. As the

efficiency of the annealing furnace decreases, the actual anneal energy increases. The actual anneal energies for several furnace efficiencies are tabulated in Exhibit 8.3.

The continuous hydrostatic extruder is smaller physically than a multiple station conventional wire drawing machine. This in itself constitutes a savings in energy by a reduction in the physical area which must be heated or cooled and lighted.

The continuous hydrostatic extruder uses one die compared to several used by conventional wire drawing. Although this is a cost factor, in the extreme it can be considered an energy savings by reducing the number of dies that need to be produced.

8.9 Review of Hydrostatic Extrusion Development - Pre (1972) and Post (1979) "Oil Embargo" :

8.9.1 Pre (1972) "Oil Embargo"

After six years of development effort at ERC, a joint study by ERC and PECC of progress to date was conducted in 1972 on hydrostatic extrusion development. A specific consideration was the implementation of hydrostatic extrusion at the Atlanta cable plant. At this time there was available space in Atlanta for expansion of production capacity and the forecast was "bullish" for the demand for copper wire. The management decision that was facing Western Electric was whether or not the Company should install conventional wire drawing equipment to meet a projected incremental demand of 55 BCF (billion conductor feet), or should they spend development dollars to perfect and install hydrostatic extrusion at the Atlanta plant.

The relevant information from the in-house study is as follows:

<u>Conventional Wire Drawing</u>	<u>Economic Variable</u>	<u>Hydrostatic Extrusion</u>
1. ---	1. Development Expense	1. \$3,225,000
2. \$1,900,000 (optimistic) \$2,050,000 (pessimistic)	2. Capital Equipment ¹	2. \$1,260,500 (optimistic) \$2,600,000 (pessimistic)

<u>Conventional Wire Drawing</u>	<u>Economic Variable</u>	<u>Hydrostatic Extrusion</u>
3.	3. Operating Costs ¹	
	PIC line	
\$535,000(total)/10BCF ²	- optimistic	\$442,000(total)/10BCF
\$546,500 /BCF	- pessimistic	\$496,000 /10BCF
\$ 48,500	- Electricity	\$ 39,000
	Pulp Line	
\$313,000(total)/10BCF ²	- optimistic	\$215,300(total)/10BCF
\$313,000 /10BCF	- pessimistic	\$249,100 /10BCF
\$ 33,200	- Electricity	\$ 26,600

- (1) The difference between the "optimistic" and the "pessimistic" estimates is due to the projected speeds attainable by the production lines.
- (2) The total demand of 55 BCF was comprised of 40 BCF of PIC insulated wire and 15 BCF of Pulp insulated wire.

Under the most optimistic conditions the following relationships were developed:

$$\begin{aligned}
 \text{(a) Net Capital Required} &= \$3,225,000 - (\$1,900,000 - \$1,260,500) \\
 &= 3,225,000 - 639,500 \\
 &= \$2,585,500
 \end{aligned}$$

$$\begin{aligned}
 \text{(b) Net Operating Savings} &= (\$535,000 - 442,000 \times \frac{40}{10} \\
 &\quad + (313,000 - 215,300 \times \frac{15}{10}) \\
 &= 372,000 + 146,550 \\
 &= \$518,500
 \end{aligned}$$

$$\text{(c) Minimum Number of years to Payback} = \frac{2,585,500}{518,500} = 5$$

Since the payback period would have been at least five years under the most optimistic conditions, WE management did not view the investment in hydrostatic extrusion attractive at that time.

8.9.2 Post (1979) "Oil Embargo"

It should be noted that in the analysis above the cost savings attributable to energy reduction was less than 10% of the overall

operating savings. Since the time of the oil embargo, and the economic effectiveness of the OPEC cartel, energy costs are close to having tripled and the potential role of hydrostatic extrusion in meeting WE's copper wire demand should be reevaluated. Concomitant with the steep rise in energy costs has been the slowing of economic growth in the industrialized nations; in particular, the demand for copper wire. Therefore, the decision alternatives are not related to meeting additional capacity requirements; the decision alternatives now pose a choice for WE management of whether or not to replace relatively new wire drawing equipment with hydrostatic extrusion equipment that offers cost savings and energy reduction. Unlike the situation involving increased capacity requirements, the "new" situation would require a huge outlay of capital that could be justified with only operating savings, i.e., there would be no capital savings over installing additional wire drawing equipment.

Two other factors of a technological nature have impacted projections of the demand for copper wire besides the cost of energy: (1) loop technology and (2) fiber optics technology. In the short term, loop electronics may have a bigger impact on copper wire demand than fiber optics. Loop electronics can be used for telecommunications between a central office and residential customers, and enable a single wire pair to handle 96 conversations instead of a single conversation.

Although the United States has been slower to apply fiber optics technology to telecommunications than other industrialized nations, several companies are beginning to develop production experience for the future. General Telephone of Indiana is installing a five kilometer inter-office trunk system in Fort Wayne. Cablecom General has installed a six kilometer aerial fiberoptic cable for its television systems with the aid of Siecor Optical Cables and Siemens Corporation. [Product Engineering, February 1979, pp.20.] The Atlanta facility of WE is also installing a fiberoptic wire production line for certain of its telecommunications applications.

With respect to hydrostatic extrusion development, WE management could follow one of several possible strategies:

- 1) plan for the adoption of hydrostatic extrusion immediately;
- 2) plan for the adoption of hydrostatic extrusion at a specified target date in the future;
- 3) postpone any further development effort indefinitely.

As part of a proposed updating of the 1972 WE study, various technical concerns would have to be investigated:

- a) In a production environment, what would be the expected die-life ?
- b) Would the wear surface of the machine be able to support high loads ?
- c) In stringing up a line, would production workers have difficulty in "jogging" the hydrostatic extruder for small size wire ? [The use of recycled wire may increase the number of breaks per shift.]
- d) Will the relative roughness of the extruded wire make it difficult to strip the insulation in the field ?
- e) Since the extruder is very fast, will a "bottleneck" be created due to a lag in "take-up" technology ?

For each of the above potential hurdles, the engineering development effort for technical proving would have to be specified, and the attendant costs projected. A key projection would be the cost per kilowatt-hour for electric power and resistance heating. This figure is expected to grow significantly in the next decade. Therefore, the total energy costs for producing, say, 600 BCF will be quite large. An estimate of the total annual energy cost for producing 600 BCF is based on the following set of calculations:

600 BCF

0.542×10^{-3} lbs./linear foot

0.178 kilowatt-hrs./lb. (conventional wire drawing)

\$0.05 per kilowatt-hr. for electrical energy

$600 \times 10^9 \times 0.542 \times 10^{-3} \times 1.78 \times 10^{-1} \times 5 \times 10^{-2} = \2.9×10^6

Hydrostatic extrusion is projected to require one-third the energy of conventional wire drawing, and, if achievable, the project savings would be \$2 million per year, plus associated labor savings.

8.10 Applicability of Results to Other Manufacturers:

The Fuchs Method has been patented and since Western Electric offers technology of this kind to other concerns on a license or royalty basis, the benefits of a perfected "production-tested" system could be extended to other firms. In the area of technology transfer and licensing, ERC has a contract with Reynolds Metals to study the feasibility of the Fuchs Method to the extrusion of aluminum tubing for refrigeration and air conditioning. A small production model of a similar invention by Fuchs, i.e., the disc machine as described in Appendix A, has also been installed in Nassau Smelting, a subsidiary of Western Electric, for making resin core solder wire. A licensing agreement for the continuous process has been reached with a Japanese firm for aluminum and copper cable. In addition, hydrostatic extrusion may have wide application in shaped wire (non-round; rectangular, square) and superconductors.

A critical entity besides Western Electric for any widespread adoption of the Fuchs Method would be the machine builder who would have to be an innovator by developing and perfecting ideas. Up to the present, there has been little involvement between WE and a machine builder. Such an undertaking would require technological risk capital - a possible role for the Department of Energy. With the appropriate contractual requirements for the promotion of licensing, a DOE sponsorship of the next level of technical "proofing" may help to advance the state of the art of hydrostatic extrusion, and, thereby, introduce an energy and cost saving technology into the wire drawing industries.

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EXHIBIT 8.1

Adiabatic versus Isothermal Process Results

Material Properties:

Melting Temperature	1083°C
Yield Strength	857 kg/cm ²
Ultimate Strength	2518 kg/cm ²
Specific Heat	34.91 kg*cm/cm ³ /°C
	and 1.0 x 10 ⁶ kg*cm/cm ³ /°C

Process Parameters:

Friction Factor (M)	0.0
Relative Land Length (4RF)	0.0
Semi-cone Die Angle	10.0 degrees
Initial Temperature	20.0°C
Fraction of the Friction	
Energy Absorbed by the Wire	1.0

Results - Adiabatic - Cp=34.91

Percent Reduction in Area	Sigma (kg/cm ²)	Pressure (kg/cm ²)	Final Temp. (°C)
10.0	917.777	212.831	26.097
15.0	960.066	271.442	27.775
20.0	1031.919	338.919	29.708
30.0	1139.886	496.343	34.218
35.0	1196.184	590.298	36.909
40.0	1253.698	696.639	39.955
50.0	1371.073	955.706	47.376
55.0	1359.514	1112.001	51.853
60.0	1415.124	1297.521	57.168
70.0	1603.171	1774.661	70.835
75.0	1690.285	2089.525	79.855
80.0	1739.524	2484.276	91.162
90.0	1828.719	3750.664	127.438
95.0	1838.505	5037.705	164.305

Results - Isothermal - Cp=1.0 x 10⁶

Percent Reduction in Area	Sigma	Pressure	Final Temp. (°C)
10	895.834	211.611	20.000
15	925.381	269.646	20.000

(Continued)

20	956.569	334.850	20.000
30	1024.458	491.473	20.000
35	1061.500	585.908	20.001
40	1100.875	693.711	20.001
50	1187.640	960.585	20.001
55	1235.659	1127.403	20.001
60	1287.311	1323.879	20.001
70	1403.878	1842.751	20.002
75	1470.563	2195.874	20.002
80	1544.785	2648.772	20.003
90	1729.528	4158.353	20.004
95	1860.825	5760.392	20.006

Exhibit 8.2

Energy Savings on Processing Energy - Wire Draw Compared to Continuous Hydrostatic Extrusion

Process	Machine Efficiency %	No. of Wires	Process Speed (M./min.)	Actual Process Energy (kg*cm/cm ³)	Energy Savings %
Conventional Wire Drawing	23	1	3045	45627.62	
Continuous Hydrostatic Extrusion	50	1	6096	17184.18	62.3
		4	1524	12348.10	72.9

Exhibit 8.3

Energy Savings on Intermediate Anneals

Process	Number of Intermediate Anneals	Furnace Efficiency %	Actual Anneal Energy (kg-cm/cm ³)
Continuous Hydrostatic Extrusion	0	-	0
Conventional Wire Drawing	1	100%	16,126.15
		50%	32,252.31
		7%	230,373.68
Anneal Energy (kg-cm/cm ³)			Energy Savings %
Continuous Hydrostatic Extrusion	Conventional Wire Drawing		
0	16,126.15		100
0	32,252.31		100
0	230,373.68		100

Exhibit 8.4

Total Energy Savings for Production of OFHC Copper Wire
Continuous Hydrostatic Extrusion compared to Conventional Wire Drawing

No. of Wires Produced	ENERGY		[kg *cm/cm ³]					Energy Savings [%]	
	Continuous Hydrostatic Extrusion			Conventional Wire Drawing					
	Process Energy	Intermediate anneal Energy		Total Energy	Process Energy	Intermediate Energy	Anneal Energy		Total Energy
8.31	1	17,184.6	0	17,184.6	45,627.6	100	16,126.1	61,753.7	72.1
						50	32,252.3	77,879.9	77.9
						7	230,373.6	276,001.3	93.7
	4	12,348.1	0	12,348.1	45,627.6	100	16,126.1	61,753.7	80.0
						50	32,252.3	77,879.9	84.1
						7	230,373.6	276,001.3	95.5

FIG.8.1 FLOW-THROUGH PROCESS.

FIG.8.2 DIRECT EXTRUSION.

FIG.8.3 INDIRECT EXTRUSION.

FIG.8.4 PRESSURE PROFILE FOR EXTRUSION .

ROD BREAKDOWN LINE (55 BCF)
2 Lines at 6,500 F.P.M.

10,000 lb.
Coils
(5/16" Dia)

5,000 lb.
Stems
(12 AWG)

CONVENTIONAL WIRE DRAWING
(Based on Atlanta Plant Facilities
-1972)

60 lb. Spools

NO. 2 WIRE DRAW FOR P.I.C. (40 BCF)
23 Lines at 5,000 F.P.M.
19 Lines at 6,000 F.P.M.

NO. 2 WIRE DRAW FOR PULP (15 BCF)
7 Lines at 6,500 F.P.M.

COURTESY OF WESTERN ELECTRIC CO.

FIG. 8.5 PLANT SYSTEM

10,000 lb.
Coils
(5/16" Dia)

P.I.C. - TANDEM (40 BCF)
23 Lines at 5,000 F.P.M.
19 Lines at 6,000 F.P.M.

60 lb. Spools

HYDROSTATIC EXTRUSION FACILITIES

PULP-NON TANDEM (15 BCF)
6 Lines at 7,500 F.P.M.
4 Lines at 12,000 F.P.M.

8.37

FIG.8.6 (COURTESY OF WESTERN ELECTRIC CO.)

FIG.8.7 (COURTESY OF WESTERN ELECTRIC CO.)

FIG.8.8 CONTINUOUS HYDROSTATIC EXTRUSION PROFILE.

FIG.8.9 ADIABATIC VS. ISOTHERMAL WIRE DRAWING.