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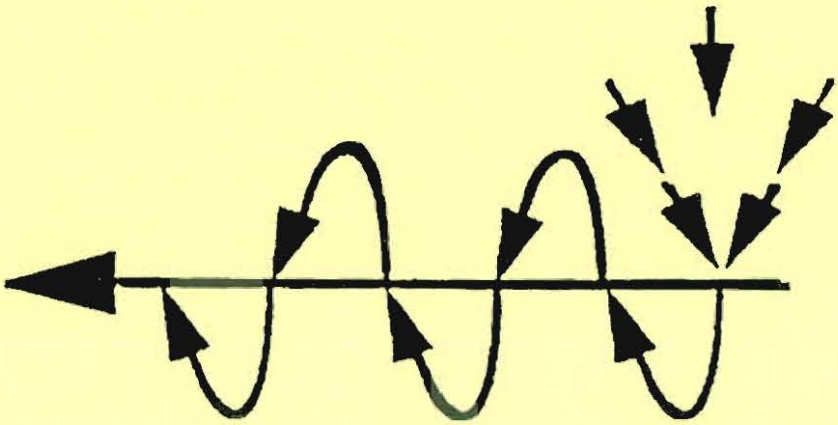
Eighth Annual

Continuous Mixer and Extruder Users' Group Meeting



20-22 September 1995
Alexandria, Virginia

Hosted by
Indian Head Division
Naval Surface Warfare Center
and
Navy Energetics Manufacturing Technology Center of Excellence

EMTC

NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

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MINUTES OF THE EIGHTH ANNUAL MEETING OF THE CONTINUOUS MIXER AND EXTRUDER USERS' GROUP

FOREWORD

The Eighth Annual Continuous Mixer and Extruder Users' Group Meeting was held in Alexandria, Virginia, on September 20-22, 1995. This meeting was hosted by the Energetics Manufacturing Technology Center (EMTC) located at Indian Head Division, Naval Surface Warfare Center (IHDIV, NSWC) and attended by representatives of the Army, Navy, Industry, and Universities involved in the development of this emerging revolutionary processing technology for energetics. International participation included representatives from France, England, Sweden, Switzerland, and Finland. Two days of technical presentations were followed by a tour of the twin screw extruder process development facility at IHDIV.

The Joint Ordnance Commanders Group (JOCG) chartered this technical interchange group in 1987 to promote the rapid development of the technology. I opened the meeting by reviewing the report authored by Mr. David Fair (Army, PBMA) which was the basis for establishing the Users' Group and which asked the group to consider whether the charter, in light of the current energetics manufacturing realities, remains valid and needed. By the end of the meeting, the consensus of the participants was that the Users' Group was beneficial and needed to continue.

As usual, all of the presentations were very informative, but I would like to highlight a few. Mr. David Fair presented an overview of the Army Program emphasizing the need for the development of this technology for specific products versus pure technology development and the move away from the use of multiple feeds. He highlighted ongoing efforts at ARDEC, Longhorn Army Ammunition Plant, and Radford Army Ammunition Plant as well as funded university efforts. Thiokol, located at Longhorn Army Ammunition Plant, has the only extruder facility in the U.S. which is used for limited production purposes of ordnance. Dr. David Dillehay from Thiokol was present to speak about their past and current processing experiences in both development and production. As the technology has matured, the focus of the meeting has transitioned from a review of facility capabilities and processing conditions to a more basic understanding of the processing science. Presentations such as "Calibration of CAMES Sensors" by Dr. Dennis Shelly (Mach I), "Non-invasive Monitoring of Segregation Processes" by Dr. Masami Nakagawa (Sandia National Laboratory), and "Rheology of Highly Filled Materials" by Dr. Dilhan Kalyon (Stevens Institute of Technology) are examples of this trend. Also, new this year was the concept of open discussions on particular technology areas important to continuous processing to maximize technical interchange. Issue areas were processing safety, rheology, and feeder accuracy. The open discussions were well attended, the participation was excellent, and they seemed to benefit all involved.

Additionally, the informal discussions during breaks and lunch were also very interesting and informative. Overall, the attendees seemed to be pleased with the scope and content of the meeting and the planning process for next year's meeting has begun. The host for the ninth annual meeting is the Highly Filled Materials Institute of Steven's Institute of Technology located in Hoboken, New Jersey. The time frame for the meeting is early summer of 1997. Any feedback, suggestions, or offers of help for organizing next year's meeting should be addressed to myself or Mr. David Fair at DSN 880-2941 or commercial 201-724-2941.

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CHARTER FOR JOCG EXTRUDER USERS GROUP

The Joint Ordnance Commanders Group (JOCG) has sanctioned the meeting of technical managers, engineers, and scientists involved in the continuous mixing and/or extrusion of energetic materials. This group of individuals from government, industry, and academia will meet for the purpose of providing a forum to discuss common problems with facility design, equipment, processing, quality, and safety. The goal of this group is to better understand how these problems can be resolved so that this technology can be fully implemented in the manufacture of propellants and explosives. This group shall be known as the "Continuous Mixer and Extruder Users' Group," and will meet annually.

There will be joint responsibility for chairmanship of the group shared by at least two service representatives (i.e., Army and Navy co-chairs, or Navy and Air Force co-chairs, or Army and Air Force co-chairs). The responsibility for the meeting and its site may be delegated to one of the sitting co-chairs each year, and then alternated from year to year if desired.

The material presented at the "Continuous Mixer and Extruder Users' Group" meeting will be unclassified. The meeting must be completely open to encourage as much dialogue as possible between participating parties. Foreign nationals who have processing experience with automated continuous mixing or extrusion operations for energetic materials are encouraged to attend. Guarding national security interests is the responsibility of the host activity and each presenter.

Participants at Eighth Annual Continuous Mixer and Extruder User's Group Meeting, Marriott Courtyard, Alexandria, Virginia, 20-22 September 1995.

Photo, next page: Participants tour the twin screw extruder process development facility at Indian Head Division, Naval Surface Warfare Center, Indian Head, Maryland.

Eighth Annual Meeting
Continuous Mixer and Extruder Users' Group

Agenda

September 20, 1995

0800 - 0900	Registration	
0900 - 0910	Welcome	John Brough, EMTC, IHDIV, NSWC
0910 - 0920	Overview of Navy Programs	Kirk Newman, IHDIV, NSWC Yorktown Detachment
0920 - 0930	Army Program to Implement Twin Screw Processing in the Manufacture of Energetics	David Fair, PBMA
0930 - 0950	Continuous Processing of Lova Gun Propellant	Richard Muscato, IHDIV, NSWC
0950 - 1010	Injection Loading SMX-13 Into Detonation Cord	Steven Jones, IHDIV, NSWC Yorktown Detachment
1010 - 1030	Status Review of Twin Screw Extruder Facility at LHAAP	P.T. Asher/Dr. David Dillehay, Thiokol Corporation
1030 - 1100	Coffee Break	Washington Room
1100 - 1130	Manufacture of PVC Propellant at TRW	Jeff Wood, TRW
1130 - 1150	Advanced Gun Propellants - TSE Processable?	Ronald Simmons, IHDIV, NSWC
1200 - 1300	Lunch (New York Avenue Deli Buffet)	Courtyard Cafe
1300 - 1315	Water Jet Cutting of Energetic Materials	Lee Estabrook, Estabrook and Associates
1315 - 1330	Incident Investigations Regarding Continuous Granulator/Extruder	Rodney Lucas, TRW
1330 - 1350	Processing Scale-up of a Filled System	Dr. David Bigio, University of Maryland at College Park
1350 - 1410	Calibration of CAMES (tm) Sensors - Technical Update	Dr. Dennis Shelly, MACH I, Inc.
1410 - 1430	Non-invasive Monitoring of Segregation Processes	Masami Nakagawa, Sandia National Laboratory
1430 - 1500	Group Photograph	
1500 - 1530	Soda Break	Washington Room
1530 - 1630	Open Discussions	
	Safety Issues (Washington Room)	David Fair, PBMA Dr. Jim Baker, UPCo
	Rheology (Jefferson Room)	Andrea Chow, Lockheed Dr. Dilhan Kalyon, SIT
1700 - 1900	Welcome Mixer	Club Room

September 21, 1995

0900 - 0920	Overview of SERDP/CAME Program	Kirk Newman, IHDIV, NSWC Yorktown Detachment
0920 - 1020	Continuous Processing of Composite Propellants	Eric Giraud, SNPE Connie Murphy, IHDIV, NSWC
1020 - 1030	Lessons Learned - Feeding Solids	David Fair, PBMA
1030 - 1100	Coffee Break	Washington Room
1100 - 1130	Feeder Variance Limitation for Continuous Mixers	John Curry, Werner & Pfleiderer
1130 - 1200	Comparison of Continuous and Batch Processing of Extruded Double Base Propellants	Robert Thompson, AOT, Inc.
1200 - 1300	Lunch (Italy Buffet)	Courtyard Cafe
1300 - 1330	On-line and Batch Monitoring Utilizing NIR Infra-red	Sean Knepper, LT Industries
1330 - 1400	Rheology of Highly Filled Materials	Dr. Dilhan Kalyon, Stevens Institute of Technology (SIT)
1400 - 1430	Twin Screw Extrusion Flow of Highly Filled Materials	Dr. Dilhan Kalyon, SIT
1430 - 1500	Soda Break	Washington Room
1500 - 1520	Die Design Considerations for Continuous Extrusion	James Kowalczyk, Shear Tool
1520 - 1530	Upgrade of the NSWC, IHDIV Facility	Richard Muscato, IHDIV, NSWC
1530 - 1630	Open Discussions:	
	Feeder Accuracy Determination (Washington Room)	Mitch Gallant, IHDIV, NSWC Eric Giraud, SNPE
	Benefits of Simulation (Jefferson Room)	Dr. Dilhan Kalyon, SIT

September 22, 1995

0800 - 1000	Facility Tour at NSWC-IHDIV for Group 1 (Meet at Bldg. 62 Upstairs Conference Room)	CPOCP Team, IHDIV, NSWC IHDIV, NSWC
1000 - 1200	Facility Tour at NSWC-IHDIV for Group 2 (Meet at Bldg. 62 Upstairs Conference Room)	CPOCP Team, IHDIV, NSWC IHDIV, NSWC

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20 - 22 SEPTEMBER 1995

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Eighth Annual

Continuous Mixer and Extruder Users' Group Meeting

PRESENTATIONS

Eighth Annual Meeting
Continuous Mixer and Extruder Users' Group

Presentations

September 20, 1995

1.	Overview of Navy Programs	Kirk Newman, IHDIV, NSWC Yorktown Detachment
2.	Army Program to Implement Twin Screw Processing in the Manufacture of Energetics	David Fair, PBMA
3.	Continuous Processing of Lova Gun Propellant	Richard Muscato, IHDIV, NSWC
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6.	Advanced Gun Propellants - TSE Processable?	Ronald Simmons, IHDIV, NSWC
7.	Processing Scale-up of a Filled System	Dr. David Bigio, University of Maryland at College Park
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September 21, 1995

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17.	Twin Screw Extrusion Flow of Highly Filled Materials	Dr. Dilhan Kalyon, SIT
18.	Die Design Considerations for Continuous Extrusion	James Kowalczyk, Shear Tool

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	Feeder Accuracy Determination (Washington Room)	Mitch Gallant, IHDIV, NSWC Eric Giraud, SNPE
	Benefits of Simulation (Jefferson Room)	Dr. Dilhan Kalyon, SIT

Overview of Navy Programs

Smart Processing for Smart Weapon Systems

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OVERVIEW OF NAVY PROGRAMS

STRATEGIC THRUSTS:

[1] Precision Strike with Multi-Mode Munitions

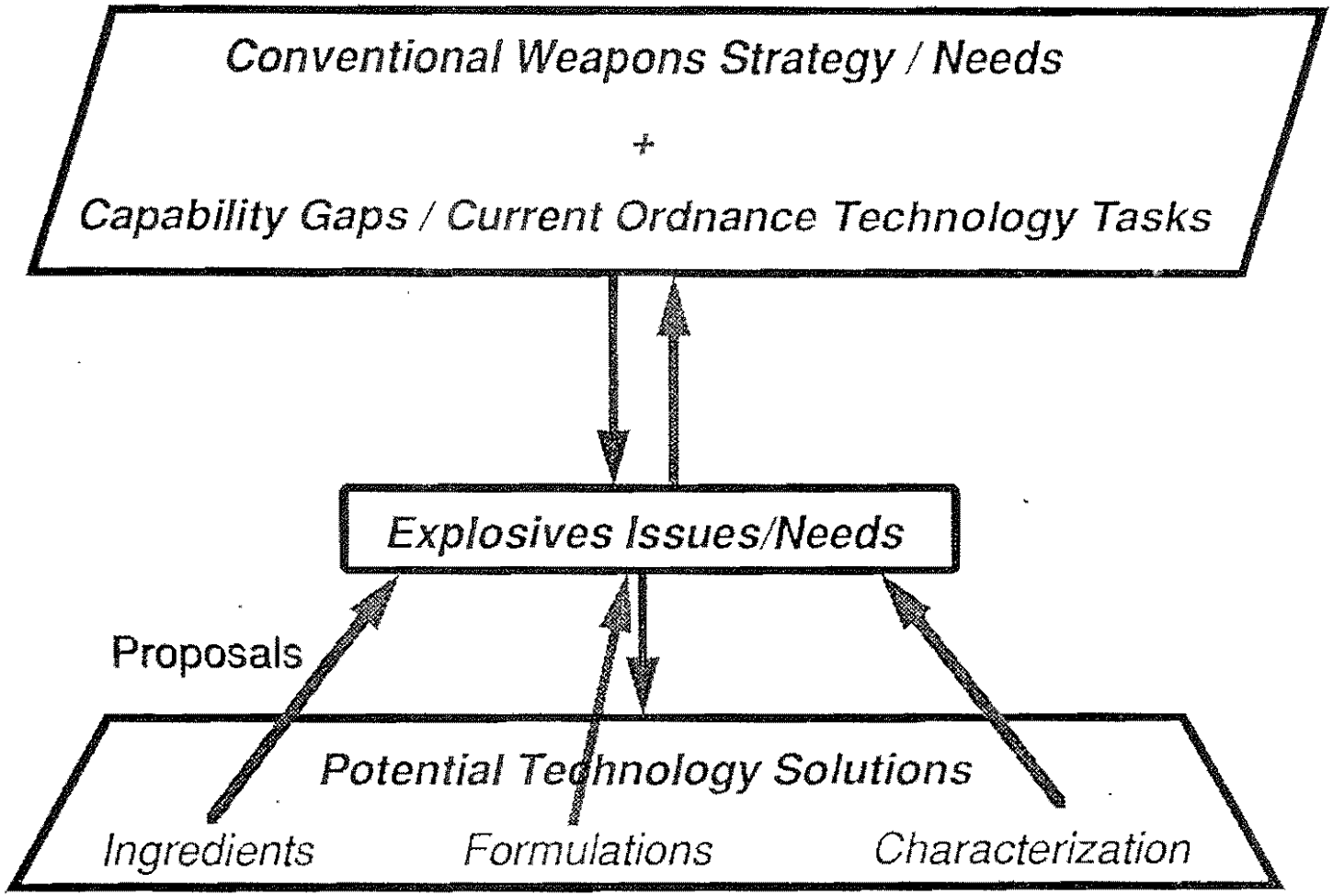
[2] Ship Self Defense

[3] Naval Surface Fire Support (NSFS)

[4] Theater Ballistic Missile Defense (TBMD)

[5] Air Superiority

ONR Air & Surface Weapons Explosives Technology Workshop



Weapon System Requirements

MIL-STD-2105B

STIMULUS	TEST PARAMETERS	PASSING CRITERIA
Fast Cook-off (FCO)	JP-5 Fuel Fire	Burning
Slow Cook-off (SCO)	Slow Heating, 6°F/HR	Burning
Bullet Impact (BI)	Three 50 cal Bullets	Burning
Fragment Impact (FI)	Steel Cubes	Burning
Sympathetic Detonation (SD)	Detonation of Round Adjacent to Like Round	No Propagation

IM Definition

Munitions that reliably fulfill performance, readiness and operational requirements on demand, but which <u>minimize the probability of inadvertent initiation and severity of subsequent collateral damage</u> when subjected to unplanned stimuli such as heat, shock and impact.

MIL-STD-2105B, 1994 (Hazard Assessment Tests for Non-Nuclear Munitions)

FUTURE GUN SYSTEMS

- HIGHER MUZZLE ENERGY
- HIGHER MUZZLE VELOCITIES
- HIGHER LAUNCH ACCELERATIONS
- HIGHER RATE OF FIRE
- GUIDED MUNITIONS
  SUBMUNITIONS
- ELECTRONIC FUZING

Scope of Project

Develop Undersea Warhead and Explosive Technologies which will Provide New Capabilities to Undersea Weaponry

- Explosive Ingredients
- Explosive Formulations
- Detonation Processes
- Target Interaction
- Fuzing/Safe and Arm
- Warhead Concepts & Performance Assessment

IM Technology Goals

- Increased Performance
- Reduced Cost
- Maintain/Improve IM Response
- Green Energetics
  - Production
  - In Use/Test
  - Demil

OVERVIEW OF NAVY PROGRAMS

CONCLUSIONS:

ALL PROGRAM OFFICES WANT MORE "BANG FOR THE BUCK" AND ARE HELD TO THE "IM" CONSTRAINT OF A "WOODEN BULLET" AND NOBODY WANTS AN "ENVIRONMENTAL LIABILITY."

ENERGETIC FORMULATIONS WILL BE HIGHLY FILLED THERMOSETTING (AND PREFERABLY THERMOPLASTIC) ELASTOMERIC MATERIALS WHOSE NITRAMINE HAS HIGH ENERGY DENSITY AND WHOSE BINDER PROVIDES SPECIFIC MECHANICAL PROPERTIES. THE APPARENT VISCOSITY OF SUCH MATERIALS WILL BE HIGHER THAN TODAY'S PBX (> 15 kp).

THEREFORE, PROCESSING WILL REQUIRE HIGH SHEAR RATE MIXING OPERATIONS. FURTHERMORE, THE MOMENTUM, MASS, AND HEAT TRANSFER CONSIDERATIONS CAN NO LONGER BE ASSUMED BECAUSE FLOW IN MORE NARROW CHANNELS OR THROUGH MORE COMPLEX GEOMETRIES WILL BE REQUIRED. INTELLIGENT PROCESS CONTROL OF AUTOMATED PROCESSES WILL EVENTUALLY BE A NECESSITY.

Overview of Army Program

Continuous Mixer and Extruder
User's
Group Meeting

20-22 September 1995

David Fair

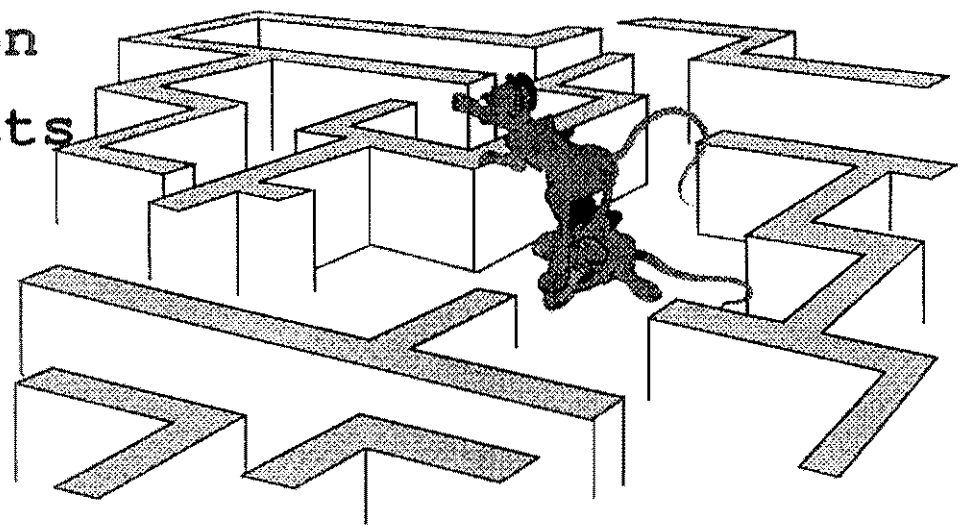
Advanced System Integration
Division

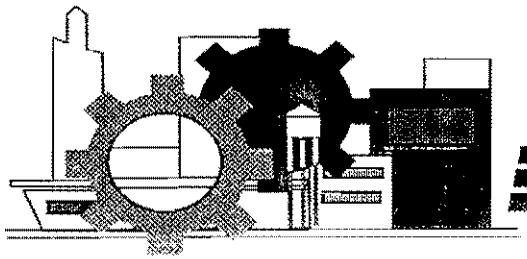
Army Program Directions

Away From the Use of Multiple Feeds

Away from Technology Development

Towards Application
to Specific Products





Product Lines

Propellants

- Highly Filled LOVA Type
  - » M43
- TPE Propellants for Tanks and Artillery
- Solventless Propellants for Tanks and Rockets

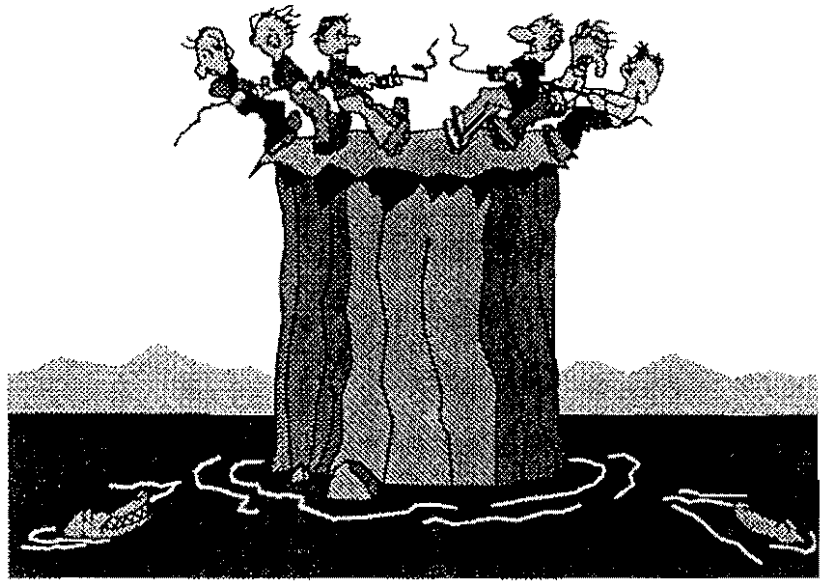
Explosives

- PAX
- Black Powder and Black Powder Substitute
- TPE Explosives

Pyrotechnics

- Flares

Activities



ARDEC

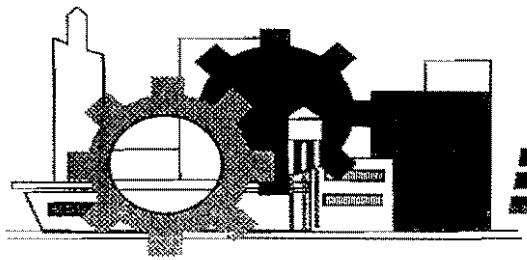
- Inert Proveout Initiated
- Program to Process Bofors Feed Stock

Longhorn Army Ammunition Plant

- Final Equipment Design is Being Prepared
- Processing on Live Formulations Demonstrated

Radford Army Ammunition Plant

- Transfer of Shear Rolling Mill and Twin Screw Extruder to Radford AAP



Activities

Goodness of Mixing

- M43 Propellant
- M30A1 Propellant
- TPE Propellant
- Bofors M39 Propellant
- Portable Goodness of Mixing Device

Rheology

- Zeren Research High Shear Rate Rheometer
  - » Phase II funded
- M43 Rheology Study -- NSWC Indian Head and Stevens Institute of Technology

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INDIAN HEAD DIVISION
Naval Sea Systems Command

Eighth Annual Continuous Mixer and Extruder Users' Group Meeting
20-22 September 1995

Continuous Processing of Lova Gun Propellant on a Twin Screw Extruder

Richard S. Muscato
Connie Murphy
Sharperson Johnson
William Newton
Carlos J. Delgado

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Agenda

- Background
- Objectives
- Facility Description
- Experimental Approach
- Tests Performed/Results
- Conclusions

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Background Information

- Effort funded by IHDIV, NSWC
- Lova Grain Trials in 1991
- Lova Slit Die Rheometer Trials in 1993
- Lova Grain Trials in 1993

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Objectives

- Process Lova in a Twin Screw Extruder
- Further define Lower and Upper Processing Parameters in a 40 mm Twin Screw Extruder
- Process "Quality" Lova Grain
- Evaluate Quality of Lova Grains
- Compare Twin Screw Processed Lova to Batch Processed Lova using the same Analysis Techniques

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Facility Description

- Pilot Scale Process Development Facility
- Werner & Pfleiderer ZSK 40 mm Twin Screw Extruder
- Five Feed Stream Capability to the Extruder
  - Three Liquid Feed Systems
  - Two Solid Feeders
- Two Temperature Control Units for Controlling Extruder Barrel Temperature
- On-Line Infra-red Thermometer
- Data Acquisition System

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Experimental Approach Preliminary Work

- Water Extraction Solid Preblending Process

- Lova Processed through an adjustable Slit DieRheometer using a Twin Screw Extruder

  Design of Experiments to evaluate six Processing Parameters:

  - Temperature Profile
  - Total Throughput
  - Solvent Concentration
  - Screw Configuration

  Devolatilization

  Solid Preblending Method

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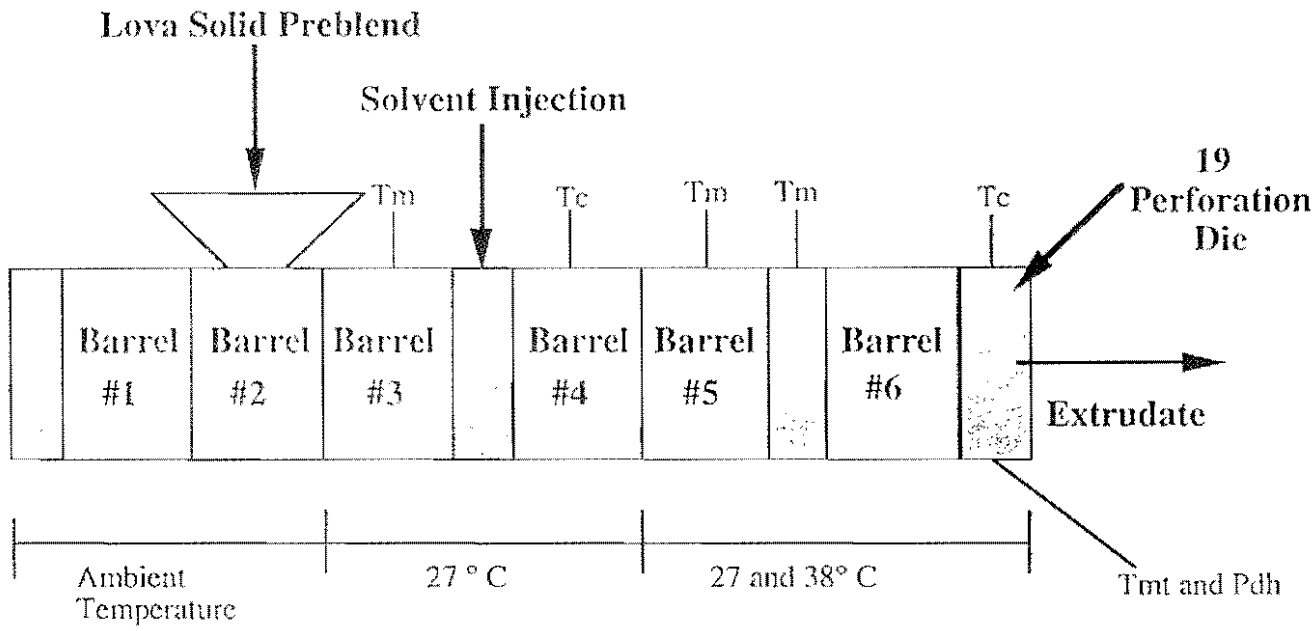
Barrel Configuration



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Experimental Approach

- Design of Experiments (DOE) used to minimize cost and maximize results
- Six Processing Trials at Following Parameters

Processing Parameter	Lower Value	Upper Value
Temperature Profile:	27/27 °C (80/80 °F)	27/38 °C (80/100 °F)
Total throughput:	5.5 kg/hr (12 lb/hr)	8.2 kg/hr (18 lb/hr)
Solvent concentration: (by weight)	12.0 %	13.0 %
Screw configuration:	Less intense (4 pairs of kneading blocks)	More intense (6 pairs of kneading blocks)

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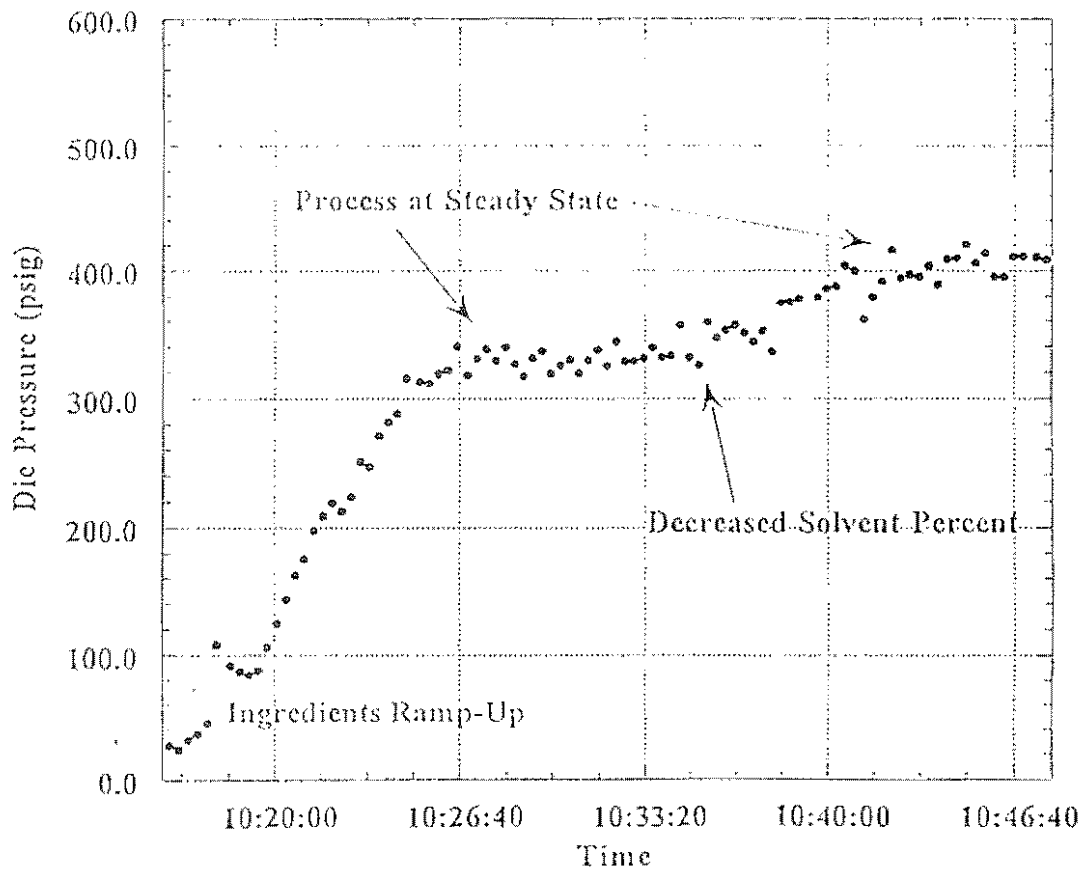
Effect of Solvent Concentration on Die Head Pressure



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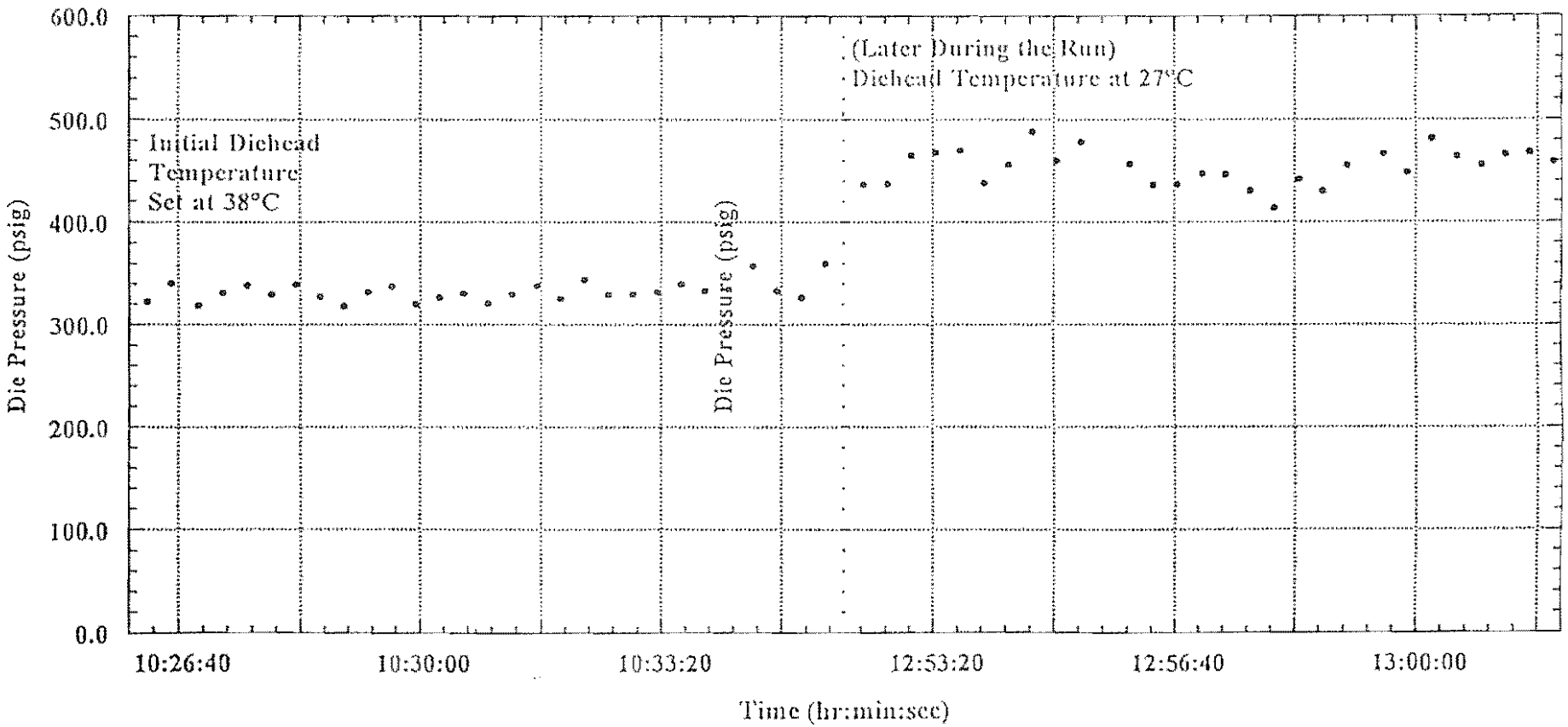
Effect of Temperature on Die Head Pressure



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Tests Performed

Tests/Analysis Techniques Used

- Scanning Electron Microscope (SEM)
- Percent Composition(% Comp)
- Heat of Explosion (HOE)
- Density
- Dimensional Analysis
- 200 cc Closed Bomb Test

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Tests Performed

Samples Taken:

29 Samples for SEM

4 Samples for % Comp, HOE, Density

2 Samples for Dimensional and
200 cc Closed Bomb Tests

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Tests Performed

Scanning Electron Microscope (SEM)

SEM Ranking Factors	No. of Regions	Points
RDX-rich Regions	0	0
	1-3	2
	> 3	4
Binder-rich Regions	0	1
	1-3	2
	> 3	3
No Porosity		0
Porosity Present		2

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Processing Parameters and SEM Values

Time	Total Thrghput	Solvent % (by weight)	Temp Profile	Screw Config	SEM Value
11:36	5.5 kg/hr (12 lb/hr)	12	27/38 °C (80/100 °F)	6 KB	1
11:54	6.4 kg/hr (14 lb/hr)	13	27/38 °C (80/100 °F)	6 KB	1
12:25	8.2 kg/hr (18 lb/hr)	13	27/38 °C (80/100 °F)	6 KB	3
12:35	8.2 kg/hr (18 lb/hr)	12	27/38 °C (80/100 °F)	6 KB	5
12:59	8.2 kg/hr (18 lb/hr)	12	27/27 °C (80/80 °F)	6 KB	5
13:21	5.5 kg/hr (12 lb/hr)	12	27/27 °C (80/80 °F)	6 KB	5

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Test Results

SEM Values = 1

Percent Compostion - Nominal

HOE within Spec

Density within Spec

Dimensional Analysis within Spec
except for Average Web

Closed Bomb Testing: % RQ lower than
Average Spec Values

73 and 74 versus 79.0 - 83.5 % RQ

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Conclusions

- Small Scale Water Extraction Process Developed
- Narrowed Processing Parameters for Processing Lova Nitramine Gun Propellant on a Twin Screw Extruder
- Lova grains produced in a Twin Screw Extrude had better SEM results (SEM = 1) as compared to Batch processd Lova
- Processed "Quality", well mixed Lova in a Twin Screw Extruder

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Acknowledgements

Mitch Gallant - Experimental design input

Ted Fillman - Manufacturing of solid preblend

Suzanne Wolfe - SEM analysis

Rich Nicol - SEM analysis

Ashley Johnson - Input on closed bomb results

Ron Simmons - Input on closed bomb results

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Eighth Annual Meeting
of the
Continuous Mixer
and
Extruder Users' Group

INJECTION LOADING SMX-13 INTO DETONATION CORD

STEVEN JONES
NSWC/IHDIV Yorktown
20 SEPTEMBER 1995

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INTRODUCTION

Surf Zone ATD Team included the following:

NSWCIHDIV - Program management & Braiding Machine

NSWCIHDIV at White Oak - Program Management & Testing

NAWC at China Lake - Formulator & Injection Loader

NSWCIHDIV at Yorktown - Scale up & Injection Loader

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OBJECTIVE

Replace the current SX-2 array with an SMX-13 array

- *Scale-up the explosive from 25 grams to 250 lbs*
  - *Perform Compatibility and Safety Tests on Explosive*
  - *Perform Mechanical Property Tests on Explosive*
  - *Perform Viscosity/Pot Life Studies*
- *Modify Injection Loader Machine To Load Detonation Cord*
  - *Investigate Alternative Load Methods*
- *Injection Load 1600 Feet of Detonation Cord*

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APPROACH

Scale-up Explosive

25 gram mix

VTS, Friction, Impact

400 gram mix

DSC, VTS, ARC, Impact, Friction, ESD, Critical Temperature

20 pound mix

I/L Run, Mechanical Property Tests, Pot Life Study
(200 Feet of Detonation Cord)

250 pound mix

I/L Run, Mechanical Property Tests, Pot Life Study
(1600 Feet of Detonation Cord)

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APPROACH

Modify Injection Loader

Install Platform for 30 Gallon B/P Mixer Bowl

Fabricate Temperature Control Chamber

Fabricate Multi-Port Load Manifold

Install Vibrating Table

Modify PLC and Operator Interface Software Program

Fabricate Methylene Chloride Stripping System

Design and Fabricate "Tube in a Tube" Load Method Fittings

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APPROACH

Load 1600 Feet of Detonation Cord

Two four person crew, 16 hour shift

Strip Methylene Chloride from Butanetriol Trinitrate

Mix 250 pounds SMX-13

Transport and Install 30 gallon mixer bowl at I/L Site

Injection Load SMX-13 into four 25 foot lengths of thin walled polyethylene tubing supported by heavy walled polyethylene tubing at one time

Cure SMX-13 Detonation Cord

Remove Outer Polyethylene Support Tubing

Ship To NSWCIHDIV For Braiding

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TECHNICAL DATA

Comparison of SX-2 and SMX-13

Summary of Data From Scale-up Batches

HMX Wash Procedure

Modification to I/L Machine and Fabrication of Supporting Equipment/Components

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EXPLOSIVE COMPARISON
SMX-13 vs SX-2

SMX-13

Physical Characteristics	
Maximum High Rate Stress	>70 psi
Maximum High Rate Elongation	>400%
Main Chemical Composition	HMX, BTTN, Aluminum, PAO
Percentage Composition	55% HMX, 10% Aluminum, 29.2% BTTN, 5.8% Binder
Density	1.752 gm/cc
Weight	417 gr/ft 350 gr/ft
Manufacturing Process	Injected loaded into polyethylene, cured, 3000 Denier over-braided with Kevlar
Sensitivity Characteristics	
Impact (50% point)	39 cm (medium)
ESD	10/10 no fires @ 0.25 Joules (medium)
Friction	20/20 no fires @750 lbs. (low)
Detonation Velocity	8,100 m/sec

SX-2

Physical Characteristics	
Maximum High Rate Stress	Approximately 30 psi
Maximum High Rate Elongation	<30%
Main Chemical Composition	RDX, Polyisobutylene, Di-(2-ethylhexyl) sebacate, PTFE
Percentage Composition	87-88% RDX, 12-13% Binder
Density	1.60 gm/cc
Weight	417 gr/ft
Manufacturing Process	Extruded, Over-wrapped with Mylar, 3000 Denier over-braided with Kevlar
Sensitivity Characteristics	
Impact (50% point)	52.4 cm (medium)
ESD	20/20 no fires @ 10 KV (medium)
Friction	20/20 no fires @ >980 lbs. (low)
Detonation Velocity	8,110 m/sec

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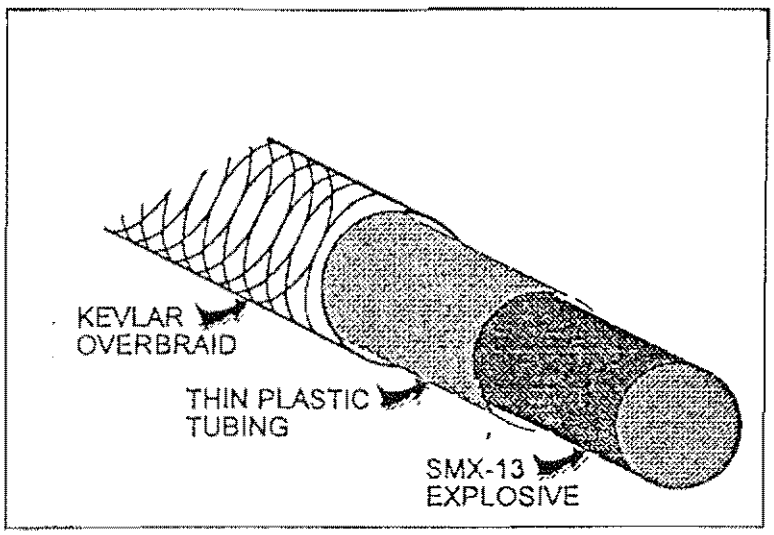
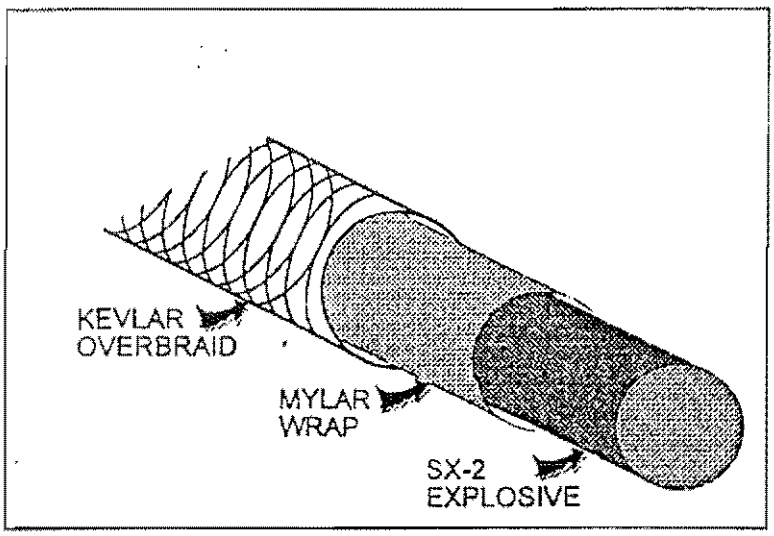


SMX-13 DETONATING CORD



SX-2 DETONATING CORD

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SCALE-UP

SMX-13 SUMMARY DATA

ATE	MIX TYPE	MIX SIZE	EOM VIS	DENSITY g/cc	VTS at 80C	VTS at 100C	VTS at 100 C	IMPACT 50 % ht	FRICTION 20/20 NF	SHORE A instant	SHORE A 15 s del	STRESS psi	ELONG %
95	HAND	25 gram	no data	no data	0.1 cc/gm	1.78 cc/gm	0.44 cc/gm	38.8 cm	235 psig	no data	no data	no data	no dat
/95	1 pint	400 gram	no data	1.730	no data	0.98 cc/gm	N/A	42.3 cm	560 psig	9	9	145	416
95	2 gallon	20 lb	14 kp	1.761	no data	no data	no data	no data	750 psig	12	12	78	315
/95	1 gallon	5 lb	4.9 kp	1.761	no data	no data	no data	no data	no data	9	7	79	423
5	30 gallon	200 lb	4.2 kp	1.741	no data	no data	no data	no data	no data	9	9	65	498
/95	30 gallon	200 lb	4.3 kp	1.751	no data	no data	no data	no data	no data	8	8	83	474

HAND MIX - FRICTION STD IS PETN = 55 psig or 60 Newtons (BAM FRICTION)
HAND MIX - VTS AT 80C TESTED 1/30/95; VTS AT 100 C TESTED ON 1/19/95 AND 1/30/95, RESP ; FOR IMPACT, RDX STD = 20.2 cm
1 PINT MIX- IMPACT RDX STD = 23.8 cm

PINT MIX- DSC ONSET OF EXOTHERM DEG

	1ST EXOTHERM	2ND EXOTHERM
Heating Rate 5 Deg/Min	180.5	268.9
Heating Rate 10 Deg/Min	187.4	276.2

PINT MIX - FRICTION STD IS PETN = 55 psig or 60 Newtons (BAM FRICTION ;BAM FRICTION = 128 Newtons
PINT MIX - ACCELERATING RATE CALORIMETRY

	1ST EXOTHERM	2ND EXOTHERM
INITIATION TEMP, (C)	139.35	189.98
INITIATION SELF-HEAT RATE (C/MIN)	0.014	0.026
MAX SELF-HEAT RATE (C/MIN)	0.158	747.4
TEMP AT MAX RATE (C)	161.42	283.84
FINAL TEMP (C)	166.81	288.75
ADIABATIC TEMP RISE (C)	27.46	98.77
TIME TO MAX RATE (MINS)	1609.45	2022.64
WEIGHT OF SAMPLE (GRAMS)	0.4149	——
PRESSURE AT INITIAL TEMP (PSI)	16.3	29.9
PRESSURE AT TEMP OF MAX RATE (PSI)	28.9	289.4
ACTIVATION ENERGY (KCAL/MOL)	40.1	——
WEIGHT OF FINAL RESIDUE (GRAM)	0.0707	——

GALLON MIX-FRICTION STD IS PETN = 55 psig or 60 Newtons(BAM FRICTI BAM FRICTION = 120 Newtons

5/14/95 30 GALLON MIX- TEST PERFORMED 6 DAYS LATER Density 1.751 g/cc Shore A = 9 (instant); 6 (15 sec delay)
Stress = 146 psig % Elongation = 522

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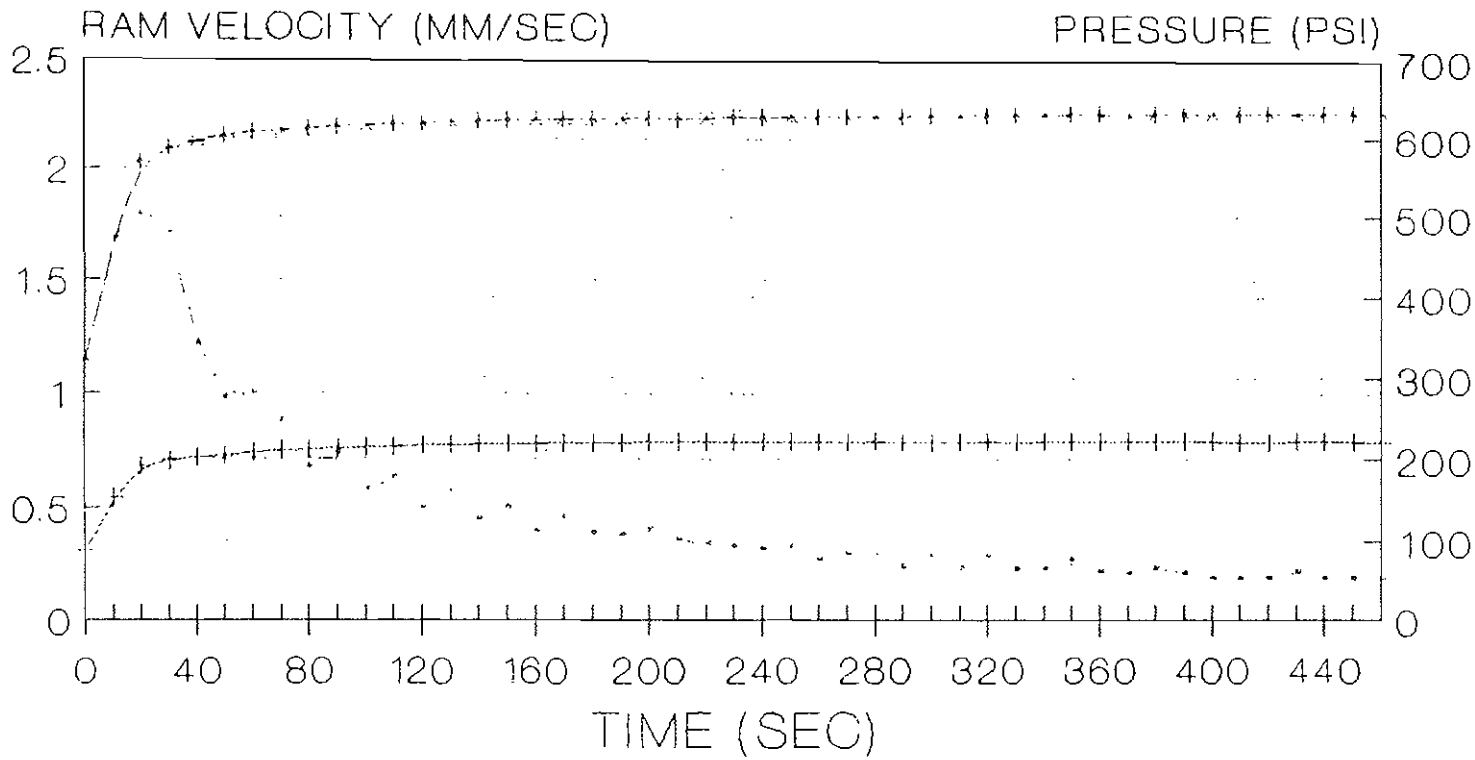
INJECTION LOADING DATA, 6/14/95

SMX-13 INTO .3175 ID TUBE INSIDE .336 ID



TIME VS RAM VEL VS CAV PRES VS HYD PRES

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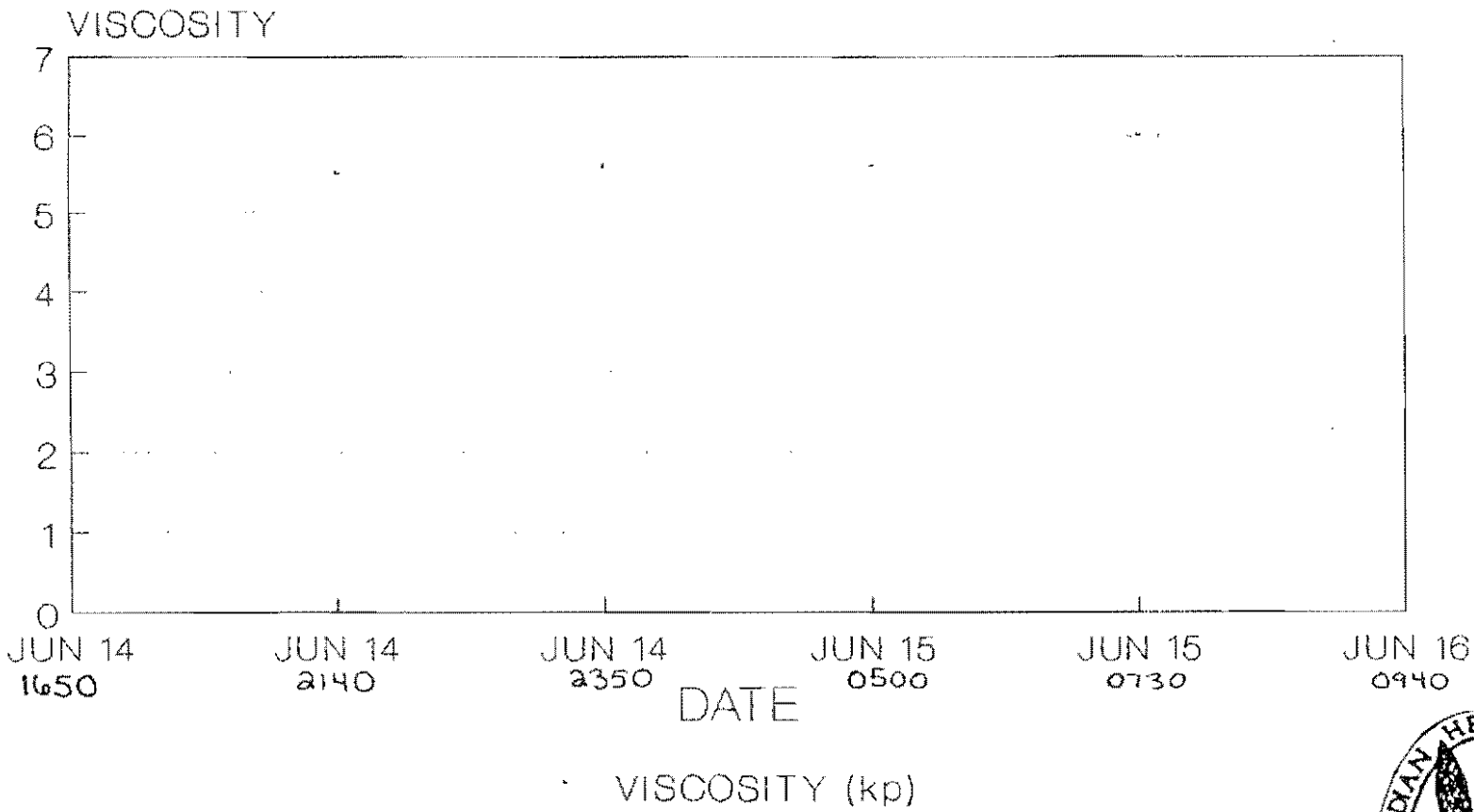
VISCOSITY VS TIME
SMX-13 EXPLOSIVE



6/14 200 LB MIX AND I/L RUN
Spendle used was HBT TC @ 2.5 rpm
All readings taken @ 52°C sample temperature

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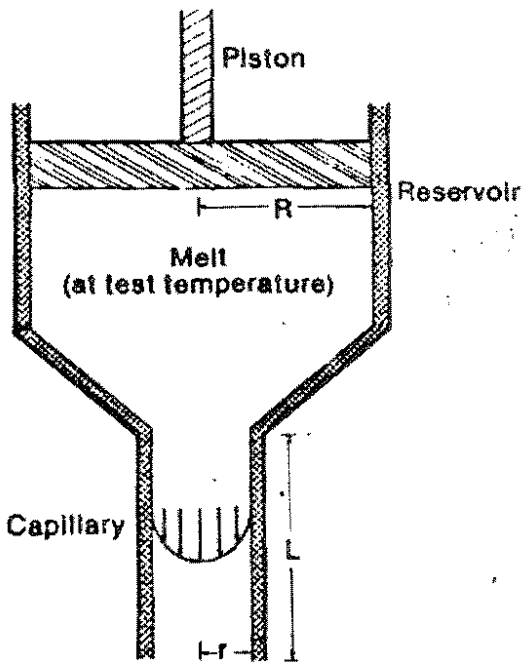
Capillary tester for volumetric flow rate



Calculating viscosity from flow-rate tests

$Q = \pi R^2 V$ (Eq. 1)

Q = Volumetric flow rate, $in.^3/sec$
R = Piston radius, in.
V = Piston velocity, in./sec

$\gamma a = \frac{4Q}{\pi r^3}$ (Eq. 2)

γa = Apparent shear rate, sec^{-1}
Q = Volumetric flow rate, $in.^3/sec$
r = Capillary radius, in.

$\tau = \frac{P \cdot r}{2L}$ (Eq. 3)

τ = Shear stress, psi
P = Pressure applied, psi
r = Capillary radius, in.
L = Capillary length, in.

$\mu = \frac{\tau}{\gamma}$ (Eq. 4)

μ = Viscosity, $lb_f \cdot sec/in.^2$
τ = Shear stress, psi
γ = Apparent shear rate, sec^{-1}

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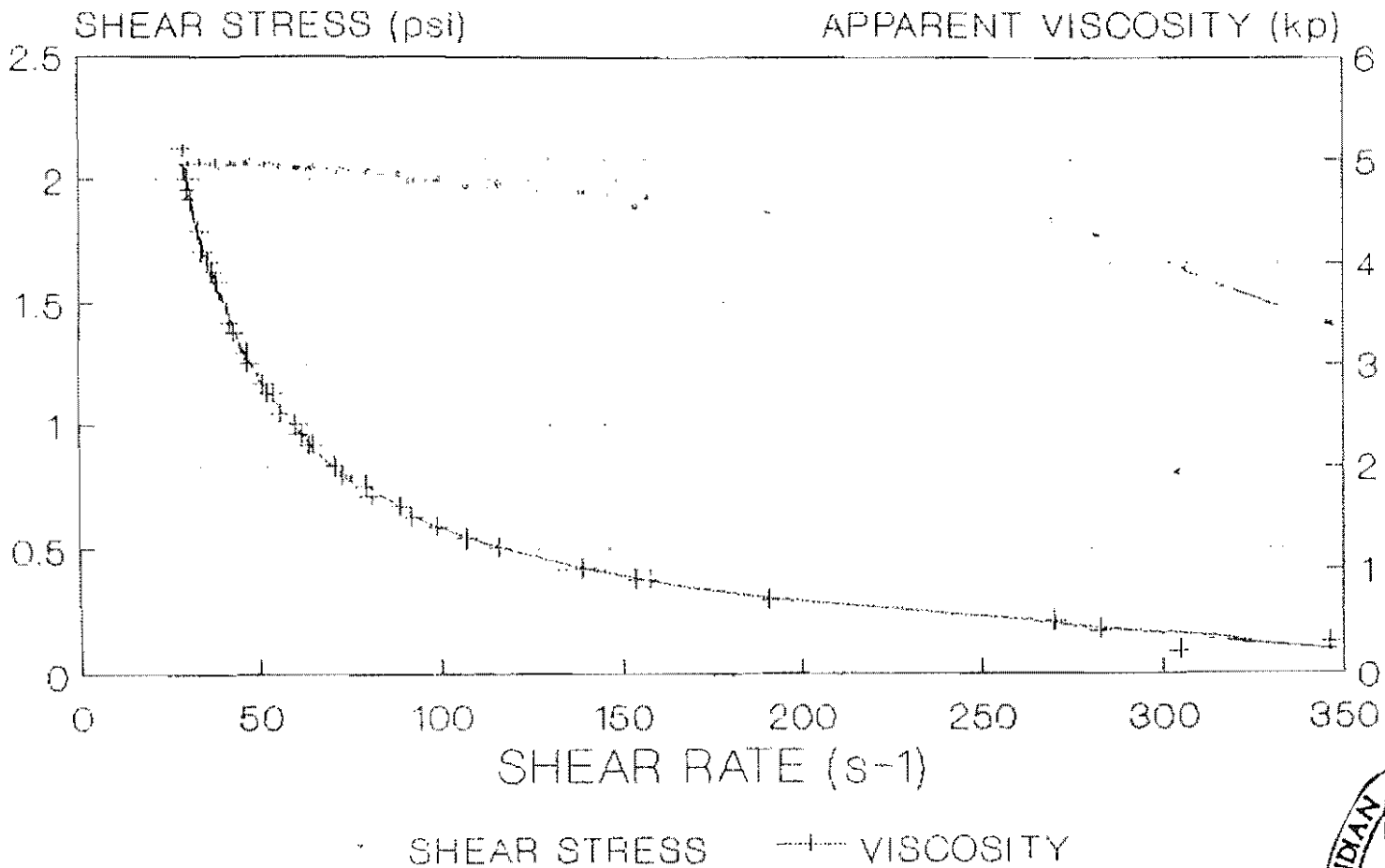
Jun 14/95 LOAD FOUR .3175 IE TUBES INTO .335 ID SUPPOR DATA

	Tag	PVI-17	RAM	RAM		CAVITY	LIFT	RAM	VOL	SHEAR	APPARENT	VISC
	Var	AO4	TRAVEL	PRESS	N/A	PRESS	PRESS	VELOCITY	FLOW	STRESS	SHEAR	kp
	EU	counts	inches	psi	psi	psi	psi	in/sec	RATE	psi	RATE	
	Low	0	-12.71	-4500	-1534.7	-1490.9	-2551.9		in3/sec		sec-1	
	High	65535	12.77	3000	992.04	983.02	1698.78					
	Jun 14/95											
	09:52:13	0	0.151	10.313	-5.718	-0.066	65.968					
	09:52:43	0	0.157	9.375	-7.298	-3.467	65.968					
	09:53:07	0	0.218	46.875	-7.929	-4.086	64.374					
	09:53:17	0	1.11	47.813	-7.929	-3.777	64.374					
	09:53:26	0	1.996	414.375	-5.718	139.403	65.437					
	09:53:56	0	1.623	9.375	-8.561	10.139	1242.35					
	09:54:19	0	1.623	9.375	-8.561	7.665	1241.82					
START LOAD —	09:54:29	0	2.384	318.75	-8.245	85.595	1233.32	0.0761	0.956301	0.799306	304.34308	0.181079
	09:54:39	0	3.248	473.438	-6.35	151.773	1233.32	0.0864	1.085734	1.417292	345.53538	0.282804
	09:54:49	0	3.952	568.125	-6.034	190.428	1234.38	0.0704	0.884672	1.778261	281.54735	0.435475
	09:54:59	0	4.627	585	-6.35	196.922	1239.17	0.0675	0.84823	1.838904	269.84952	0.469673
	09:55:09	0	5.105	594.375	-6.034	200.633	1239.7	0.0478	0.600673	1.873558	191.16425	0.67574
	09:55:19	0	5.491	601.875	-5.718	202.798	1240.76	0.0386	0.485062	1.893775	154.37113	0.845827
	09:55:29	0	5.883	605.625	-6.034	206.509	1240.23	0.0392	0.492602	1.92843	156.77068	0.848122
	09:55:39	0	6.23	609.375	-5.718	208.983	1240.76	0.0347	0.436053	1.951532	138.77405	0.969587
	09:55:49	0	6.498	612.188	-5.718	211.148	1240.76	0.0268	0.336779	1.97175	107.17998	1.268403
	09:55:58	0	6.788	614.063	-6.034	212.385	1241.29	0.029	0.364425	1.983301	115.97831	1.179047
	09:56:09	0	7.017	615.938	-6.034	213.312	1240.76	0.0229	0.28777	1.991958	91.582873	1.499633
	09:56:19	0	7.265	617.813	-6.034	214.24	1240.76	0.0248	0.311646	2.000624	99.181452	1.390766
	09:56:29	0	7.463	617.813	-6.034	215.786	1239.7	0.0198	0.248814	2.01506	79.185191	1.75454
	09:56:39	0	7.686	620.625	-6.034	216.405	1240.76	0.0223	0.28023	2.020841	89.183322	1.562311
	09:56:49	0	7.864	621.563	-6.034	216.714	1240.76	0.0178	0.223681	2.023726	71.186887	1.960073
	09:56:59	0	8.065	622.5	-5.718	217.642	1240.76	0.0201	0.252584	2.032392	80.384987	1.743219
	09:57:09	0	8.224	623.438	-5.718	217.951	1240.23	0.0159	0.199805	2.035278	63.588108	2.20682
	09:57:19	0	8.406	624.375	-5.718	218.57	1240.23	0.0182	0.228708	2.041058	72.786388	1.933412
	09:57:29	0	8.559	624.375	-5.718	219.188	1240.23	0.0153	0.192265	2.046829	61.188557	2.306378
	09:57:39	0	8.709	625.313	-6.034	219.879	1240.23	0.015	0.188496	2.043944	59.988781	2.349189
	09:57:49	0	8.871	626.25	-5.718	219.497	1240.76	0.0162	0.203575	2.049715	64.787884	2.181317
	09:57:59	0	9.011	625.313	-6.034	219.807	1241.29	0.014	0.175929	2.052609	55.989529	2.52766
	09:58:09	0	9.145	626.25	-5.718	220.116	1241.82	0.0134	0.168388	2.055495	53.589978	2.644551
	09:58:19	0	9.276	628.125	-5.402	220.425	1242.35	0.0131	0.164619	2.058381	52.390202	2.708911
	09:58:29	0	9.403	627.188	-6.034	220.116	1242.35	0.0127	0.159593	2.055495	50.790502	2.790314
	09:58:39	0	9.531	628.125	-6.034	219.807	1241.29	0.0128	0.16085	2.052609	51.190427	2.764628
	09:58:49	0	9.639	629.063	-5.718	220.116	1241.82	0.0108	0.135717	2.055495	43.191923	3.281203
	09:58:59	0	9.757	629.063	-5.718	220.116	1241.29	0.0118	0.148283	2.055495	47.191175	3.003135
	09:59:09	0	9.875	628.125	-5.718	220.734	1241.29	0.0118	0.148283	2.061266	47.191175	3.011566
	09:59:19	0	9.97	629.063	-6.034	219.497	1241.82	0.0095	0.119381	2.049715	37.992895	3.719719
	09:59:29	0	10.085	630	-5.402	220.116	1241.82	0.0115	0.144513	2.055495	45.991399	3.081477
	09:59:39	0	10.174	630	-6.034	220.116	1241.82	0.0089	0.111841	2.055495	35.593344	3.981684
	09:59:49	0	10.289	630.938	-5.402	220.734	1242.35	0.0115	0.144513	2.061266	45.991399	3.090129
	09:59:59	0	10.381	630.938	-6.034	220.116	1241.82	0.0092	0.115611	2.055495	36.793119	3.851846
	10:00:09	0	10.471	630.938	-5.718	220.734	1242.35	0.009	0.113097	2.061266	35.993269	3.948498
	10:00:19	0	10.576	631.875	-5.718	220.734	1241.82	0.0105	0.131947	2.061266	41.992147	3.384427
	10:00:29	0	10.662	631.875	-5.402	221.353	1242.35	0.0086	0.108071	2.067046	34.393568	4.143737
	10:00:39	0	10.745	630.938	-5.718	221.043	1241.82	0.0083	0.104301	2.064152	33.193792	4.287497
	10:00:49	0	10.84	631.875	-5.718	221.353	1241.82	0.0095	0.119381	2.067046	37.992895	3.751172
	10:00:59	0	10.923	631.875	-5.718	221.043	1241.29	0.0083	0.104301	2.064152	33.193792	4.287497
	10:01:09	0	10.999	631.875	-6.034	221.043	1241.82	0.0076	0.095504	2.064152	30.394316	4.682398
	10:01:19	0	11.076	631.875	-5.718	220.425	1242.88	0.0077	0.096761	2.058381	30.794241	4.608667
	10:01:29	0	11.152	631.875	-5.718	220.425	1242.35	0.0076	0.095504	2.058381	30.394316	4.669307
	10:01:39	0	11.238	632.813	-5.718	220.734	1241.82	0.0086	0.108071	2.061266	34.393568	4.132149
	10:01:48	0	11.312	632.813	-5.718	220.734	1241.82	0.0074	0.092991	2.061266	29.594465	4.802227
	10:01:58	0	11.382	632.813	-6.034	220.734	1241.82	0.007	0.087965	2.061266	27.994765	5.07664
Complete Load —	10:02:08	0	11.458	631.875	-5.718	220.116	1241.29	0.0076	0.095504	2.055495	30.394316	4.682762

459 seconds to load 88'

INJECTION LOADING DATA, 6/14/95
SMX-13 INTO .3175 ID TUBE INSIDE .336 ID



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INDIAN HEAD DIVISION

Analysis of sectioned SMX-13 Detonation Cord

SMX-13 DATA FROM 3/9/95 I/L RUN 4/14/95

Sample	Density	Length (in.)	wt. w/ Poly	wt. w/out Poly	Diameter w/ poly	Diameter w/out poly	We /
1	1.771 g/cm³	6.002	12.8 g	12.0 g	.333 in	.326 + .303	3 g/ft
2	1.770 g/cm³	5.118	11.8 g	11.0 g	.336 in	.320 + .310	39 gA
3	1.777 g/cm³	5.391	13.2 g	12.5 g	.335	.328 + .318	429 g/ft
4	1.770 g/cm³	5.228	12.0 g	11.3 g	.334	.326 + .312	400 g/ft
5	1.779 g/cm³	4.738	11.5 g	10.9 g	.336	.328 + .312	42 g/ft

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Naval Surface Warfare Center
INDIAN HEAD DIVISION

6/14/95
200 lb SMX-13
Batch # I/L RUN

TABLE 1
0.280

RAW DATA

SER #	GROUP #	DIA TUBE	LENGTH (in)	WT W/ WRAP (lbs)	WT OF EXPL (lbs)	WT/FT (gr/ft)
1	5	0.28	142	0.556	0.509566	301.4385
2	5	0.28	125.5	0.474	0.432962	289.7958
3	5	0.28	142.75	0.544	0.497321	292.649
4	5	0.28	137.5	0.53	0.485038	296.3188
5	5	0.28	141.375	0.554	0.50777	301.7042
6	5	0.28	122.5	0.494	0.453943	311.2801
7	5	0.28	107.75	0.418	0.382766	298.4024
8	5	0.28	142.625	0.552	0.505362	297.6413
9	5	0.28	132.5	0.502	0.458673	290.7859
10	5	0.28	140.25	0.534	0.488138	292.3658
11	6	0.28	135	0.516	0.471855	293.6036
12	6	0.28	140.25	0.558	0.512138	306.7404
13	6	0.28	139.25	0.536	0.490465	295.8691
14	6	0.28	139	0.534	0.488547	295.242
15	6	0.28	136	0.508	0.463528	286.3015
16	6	0.28	138	0.536	0.490874	298.7979
17	6	0.28	135	0.514	0.469855	292.3591
18	6	0.28	140	0.542	0.49622	297.737
19	6	0.28	138.625	0.528	0.48267	292.4792
20	6	0.28	139.75	0.536	0.490302	294.7123
21	7	0.28	133.5	0.526	0.482346	303.5034
22	7	0.28	139	0.548	0.502547	303.7026
23	7	0.28	135.125	0.52	0.475814	295.7932
24	7	0.28	137.375	0.538	0.493078	301.5052
25	7	0.28	138	0.548	0.502874	306.1024
26	7	0.28	139.375	0.55	0.504424	304.0169
27	7	0.28	136.875	0.542	0.497242	305.1618
28	7	0.28	132	0.516	0.472836	300.9007
29	7	0.28	131.75	0.518	0.474918	302.7989
30	7	0.28	137.25	0.54	0.495119	303.0289
31	8	0.28	138.375	0.542	0.496751	301.556
32	8	0.28	136	0.528	0.483528	298.6547
33	8	0.28	135.125	0.526	0.481814	299.5232
34	8	0.28	140	0.542	0.49622	297.737
35	8	0.28	136.5	0.536	0.491365	302.3832
36	8	0.28	139.25	0.538	0.492465	297.0756
37	8	0.28	139	0.546	0.500547	302.4939
38	8	0.28	135	0.53	0.485855	302.3149
39	8	0.28	133	0.52	0.476509	300.9581
40	8	0.28	134.25	0.524	0.4801	300.403
41	9	0.28	139	0.54	0.494547	298.868
42	9	0.28	138.625	0.546	0.50067	303.3865
43	9	0.28	133.25	0.51	0.466427	294.0379
44	9	0.28	136.5	0.538	0.493365	303.614
45	9	0.28	139.5	0.536	0.490384	295.2896
46	9	0.28	135.375	0.528	0.483732	300.1603
47	9	0.28	138.125	0.528	0.482833	293.6374
48	9	0.28	141	0.544	0.497893	296.6221
49	9	0.28	142	0.55	0.503566	297.8891
50	9	0.28	135.5	0.526	0.481692	298.6182

INDIAN HEAD DIVISION
NAVAL SURFACE WARFARE CENTER
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6/14/95 RAW DATA
200 lb SMX-13
Batch a TABLE 2
I/L Run 0.32 TAPED

SER #	GROUP #	DIA TUBE	LENGTH (in)	WT W/ WRAP (lbs)	WT OF EXPL (lbs)	WT/FT (gr/ft)	Remarks
97	10	0.32	239.5	1.378	1.296738	454.8133	
98	10	0.32	256.5	1.438	1.35097	442.4302	
91	11	0.32	123	1.16	0.683031	466.4678	THIS PIECE CUT FOR PELETSKI
91	11	0.32	113.75	0.642	0.603405	445.5986	
92	11	0.32	239	1.374	1.292907	454.4186	
93	11	0.32	123	1.152	0.675031	461.0042	THIS PIECE CUT FOR PELETSKI
93	11	0.32	115.5	0.65	0.610811	444.2335	
94	11	0.32	122	1.16	0.686908	472.9613	THIS PIECE CUT FOR PELETSKI
94	11	0.32	109.75	0.632	0.594762	455.224	
100	12	0.32	241	1.362	1.280229	446.2283	
105	12	0.32	238.5	1.366	1.285077	452.6133	
107	12	0.32	236.5	1.378	1.297756	460.9442	
113	12	0.32	248	1.406	1.321854	447.7321	
104	13	0.32	239	1.324	1.242907	436.845	
106	13	0.32	237.5	1.312	1.231416	435.5398	
110	13	0.32	233.125	1.28	1.200901	432.7179	
111	13	0.32	248.5	1.356	1.271684	429.8722	
95	14	0.32	243	1.374	1.29155	446.4693	
102	14	0.32	239	1.336	1.254907	441.0627	
103	14	0.32	239.125	1.318	1.236865	434.4941	
114	14	0.32	237.5	1.33	1.249416	441.9062	
101	15/6	0.32	75	0.428	0.402553	450.8664	LOAD PROBLEM
101	15/6	0.32	114.5	0.66	0.62115	455.6986	LOAD PROBLEM
90	15/6	0.32	121.5	0.702	0.660775	456.8398	LOAD PROBLEM
90	15/6	0.32	78.75	0.45	0.42328	451.5064	LOAD PROBLEM
108	15/6	0.32	141.75	0.824	0.775904	459.8028	LOAD PROBLEM
108	15/6	0.32	70	0.398	0.374249	449.1063	LOAD PROBLEM
99	15/6	0.32	84.25	0.48	0.451414	450.082	LOAD PROBLEM
99	15/6	0.32	143.875	0.834	0.785183	458.4292	LOAD PROBLEM
115	17	0.32	233.5	1.312	1.232773	443.4891	
116	17	0.32	233.5	1.302	1.222773	439.8916	
109	17	0.32	234	1.31	1.230604	441.7626	
112	17	0.32	229	1.264	1.1863	435.1568	
117	18	0.32	240	1.31	1.228568	430.006	
118	18	0.32	219.875	1.29	1.215396	464.3321	
119	18	0.32	233.625	1.304	1.224731	440.3601	
120	18	0.32	223.75	1.278	1.202082	451.2918	

INDIAN HEAD DIVISION
NAVAL SURFACE WARFARE CENTER
ENERGETICS

HMX WASH PROCEDURE

NSWC Naval Surface Warfare Center INDIAN HEAD DIVISION

PROJECT WORK ORDER

WORK ORDER NO.: _____ DATE: 4/21/95

PROJECT TITLE: SURF ZONE

PROJECT ENGINEER: JONES JOB ORDER: 1663350

QA___ DATA___ SAMPLE___ PHOTO___ XRAY___ BOXES___ SHIP__

Reference (a): Y46-013, Laboratory Batching Pressed Explosive Molding Powders
Y46-016, Laboratory Steam-Heated Oven Operations
Y46-029, Procedure for Drying CXM, HMX and RDX
Y46-011, Explosive Transportation

WORK:

Goal: To prepare 120 lbs of Class 5 HMX for an SMX-13 Batch on May 9 utilizing the slurry mixer in 1752

1. Obtain the class 5 HMX from building 1753 or the magazine if there isn't enough in accordance with Y46-011. The lot to use is HOL Lot 86A200-031.

2. Place water/alcohol wet HMX in the slurry mixer with 75% by weight of water. To determine the %water to use with the mix refer to this example:

A = weight of water/alcohol wet HMX = 5 lbs

A is 25% of total weight or 5 lbs = .25X
X = 20 lbs

where X= total weight of water/alcohol wet HMX plus water
B = weight of water or 75% of total weight
A + B = X

Therefore 5 + B = 20

or B = 15 lbs

3. Mix each batch at 450 rpm for 15 minutes with no heat or vacuum. Stop mixing and let sit for 2 hours. Remove bottom layer of water from slurry mixer. Pour top layer into aluminum drying pans and place them in the lab ovens or the 1248 ovens at 52 - 60 C. After drying transfer dried HMX to ice cream containers. Label the containers as "SMX-13 HMX".

Please complete no later than 5 May 95.

THANK YOU!

INDIAN HEAD DIVISION NAVAL SURFACE WARFARE ENERGETICS

BEFORE WASH PROCEDURE

NSWC Naval Surface Warfare Center INDIAN HEAD DIVISION

Brinkmann Particle Size Analyzer

SAMPLE NAME : HMX, CLASS 5, LOT 86A200-031 (#2)
FILE NAME : A:GONZ2B

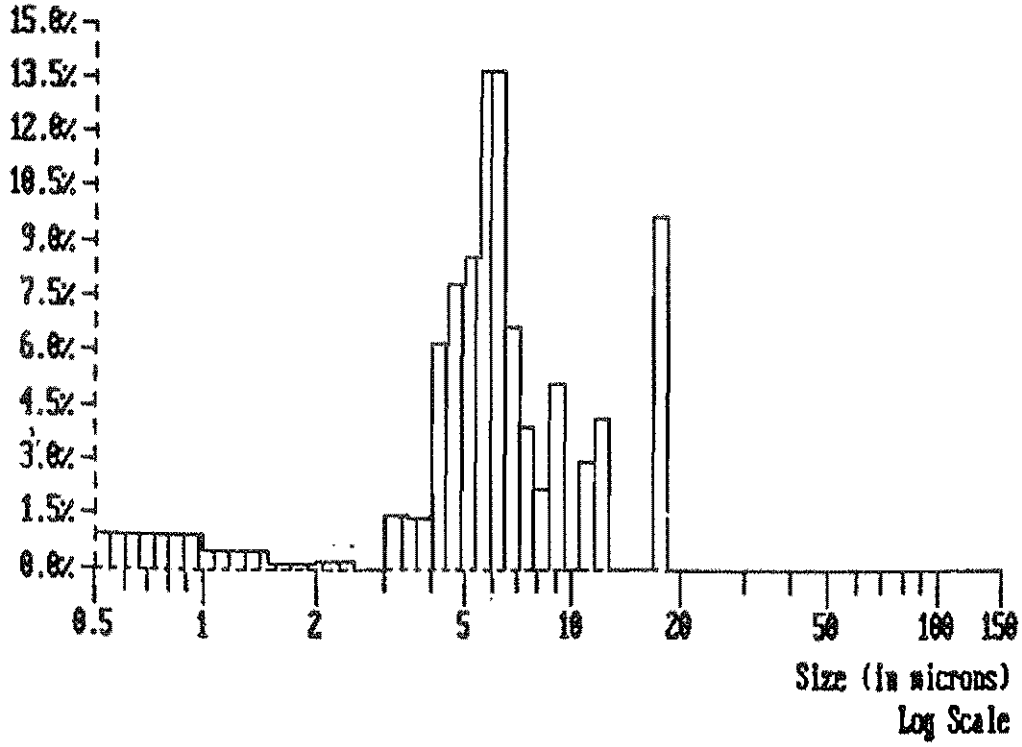
DATE	: 15/04/1994	ACQ. RANGE	: 0.5-150	COUNTS	: 14749
TIME	: 09:27	ACQ. MODE	: SAMPLE	S.N.F.	: 0.64
CONFIG.	: 1 (0.7 S1)	ACQ. TIME	: 35 SEC	S.D.U.	: 6478
CELL TYPE	: MAGNETIC (2)	SAMPLE SIZE	: 2	CONCENTR.	: 8.5E+06
SAMPLE TYPE	: REGULAR	REQ. CONF.	: None	SOLIDS	: 2.3E-0

PROBABILITY VOLUME DENSITY GRAPH

Name: HMX, CLASS 5, LOT 86A200-031 (#2)
2.3E-05 cc/ml(100.0%)
Mode at 6.01 µm
<< SCALE RANGE (µm): ADJUSTED >>

Mean(nu): 1.73µm
S.D.(nu): 1.11µm

Median : 5.87µm
Mean(vm): 6.85µm
S.D.(vm): 4.27µm
Conf(vm): 93.62 %



INDIAN HEAD DIVISION NAVAL SURFACE WARFARE CENTER ENERGETICS

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INDIAN HEAD DIVISION

AFTER WASH PROCEDURE

Brinkmann
Particle Size Analyzer

SAMPLE NAME : HMX B/5 HOL86A200-031 F/SMX-13
FILE NAME : JONES1

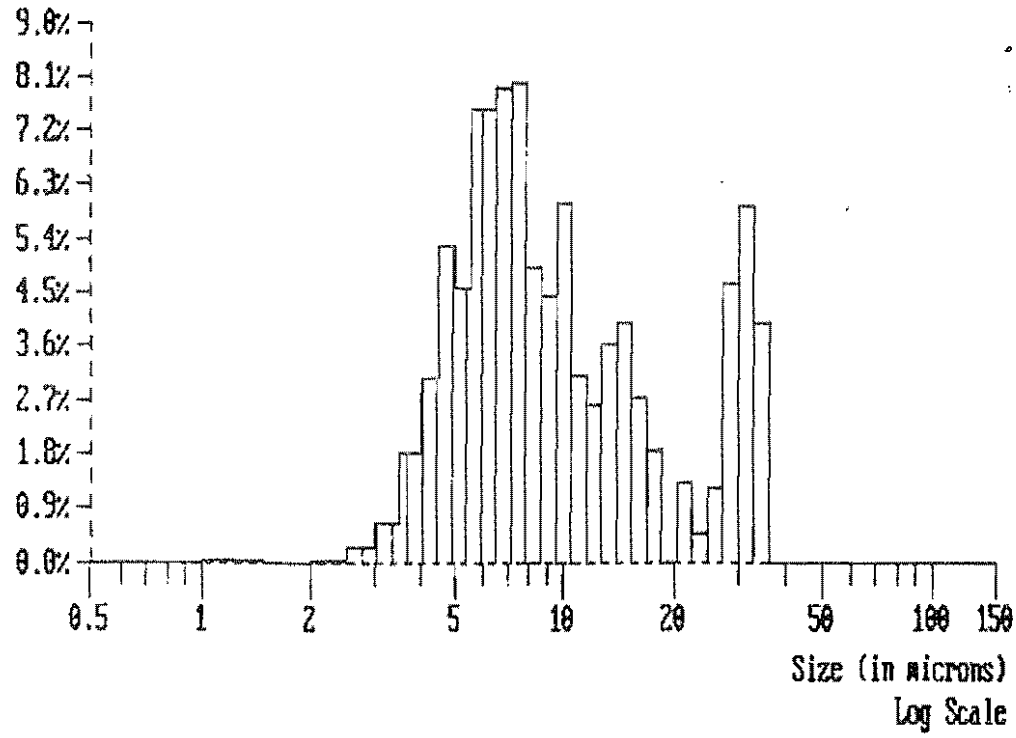
DATE	: 09/06/1995	ACQ. RANGE	: 0.5-150	COUNTS	: 34846
TIME	: 08:58	ACQ. MODE	: SAMPLE	S.N.F.	: 0.50
CONFIG.	: 1 (0.7 S1)	ACQ. TIME	: 91 SEC	S.D.U.	: 9117
CELL TYPE	: MAGNETIC (2)	SAMPLE SIZE	: 2	CONCENTR.	: 2.4E+06 #/m
SAMPLE TYPE	: REGULAR	REG. CONF.	: None	SOLIDS	: 1.2E-02 %

PROBABILITY VOLUME DENSITY GRAPH

Name: HMX B/5 HOL86A200-031 F/SMX-13
1.2E-04 cc/ml(100.0%)
Mode at 7.52 µm
<< SCALE RANGE (µm): ADJUSTED >>

Mean(nv): 4.54µm
S.D.(nv): 3.24µm

Median : 8.04µm
Mean(vm): 12.05µm
S.D.(vm): 9.14µm
Conf(vm): 70.29 %



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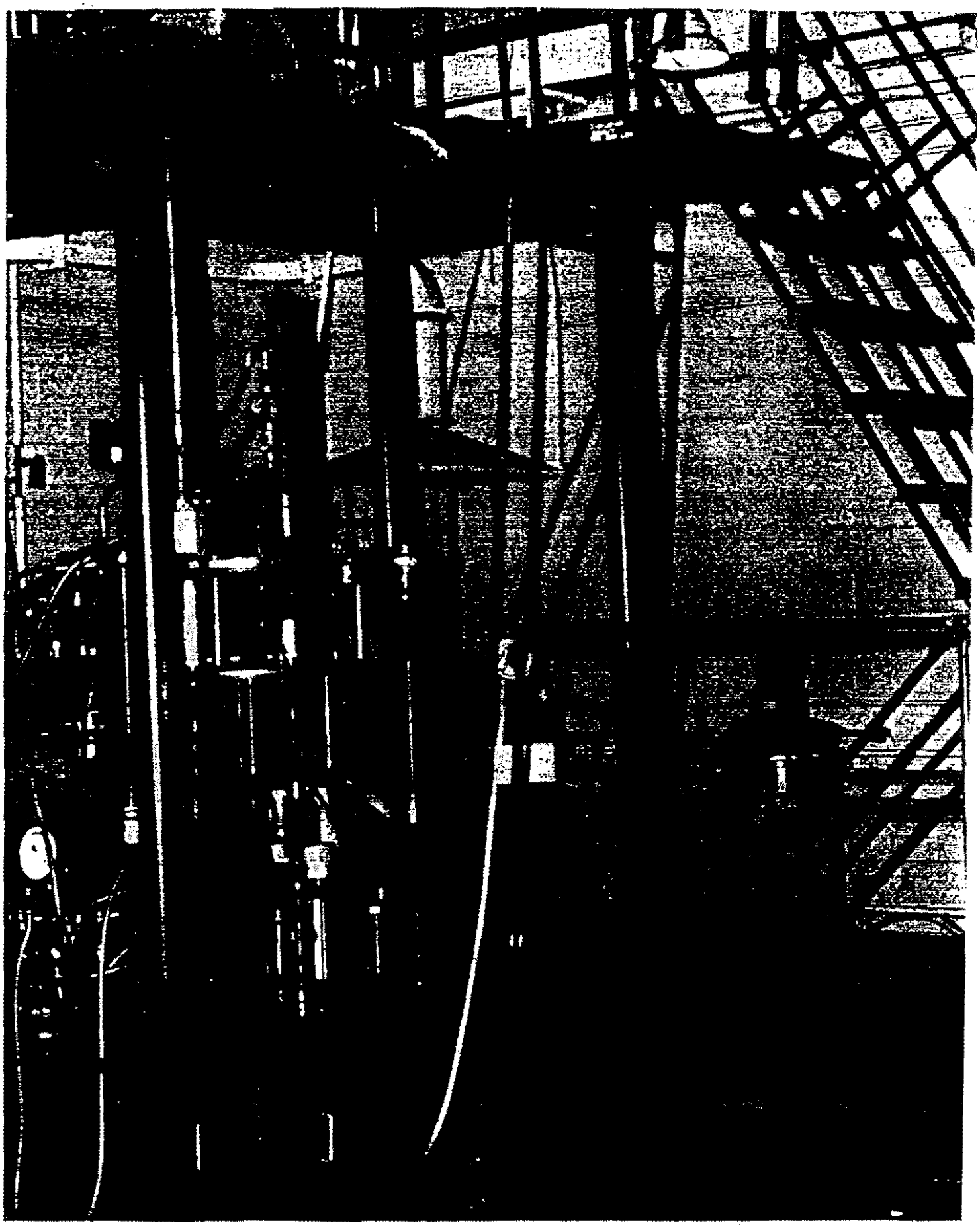

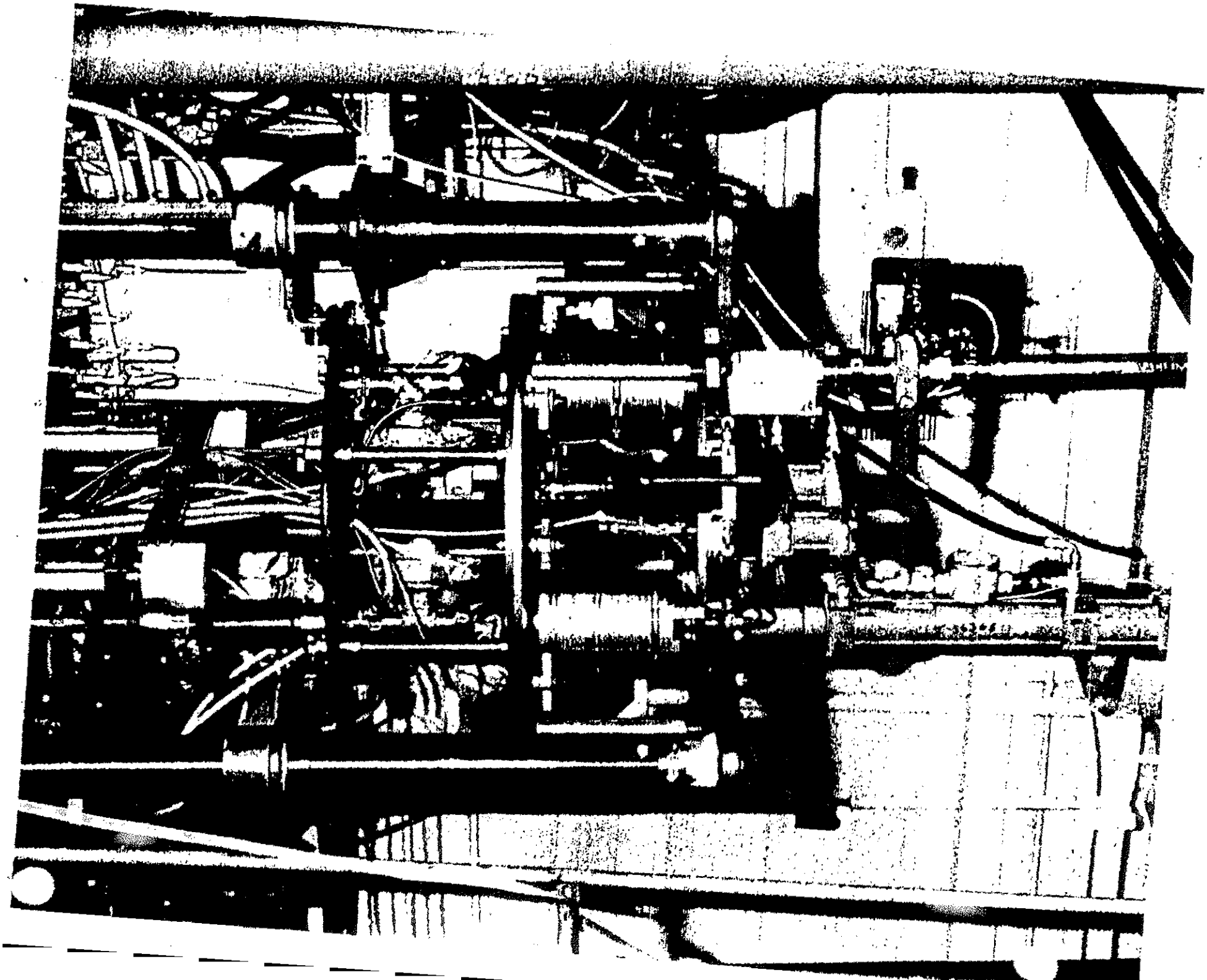

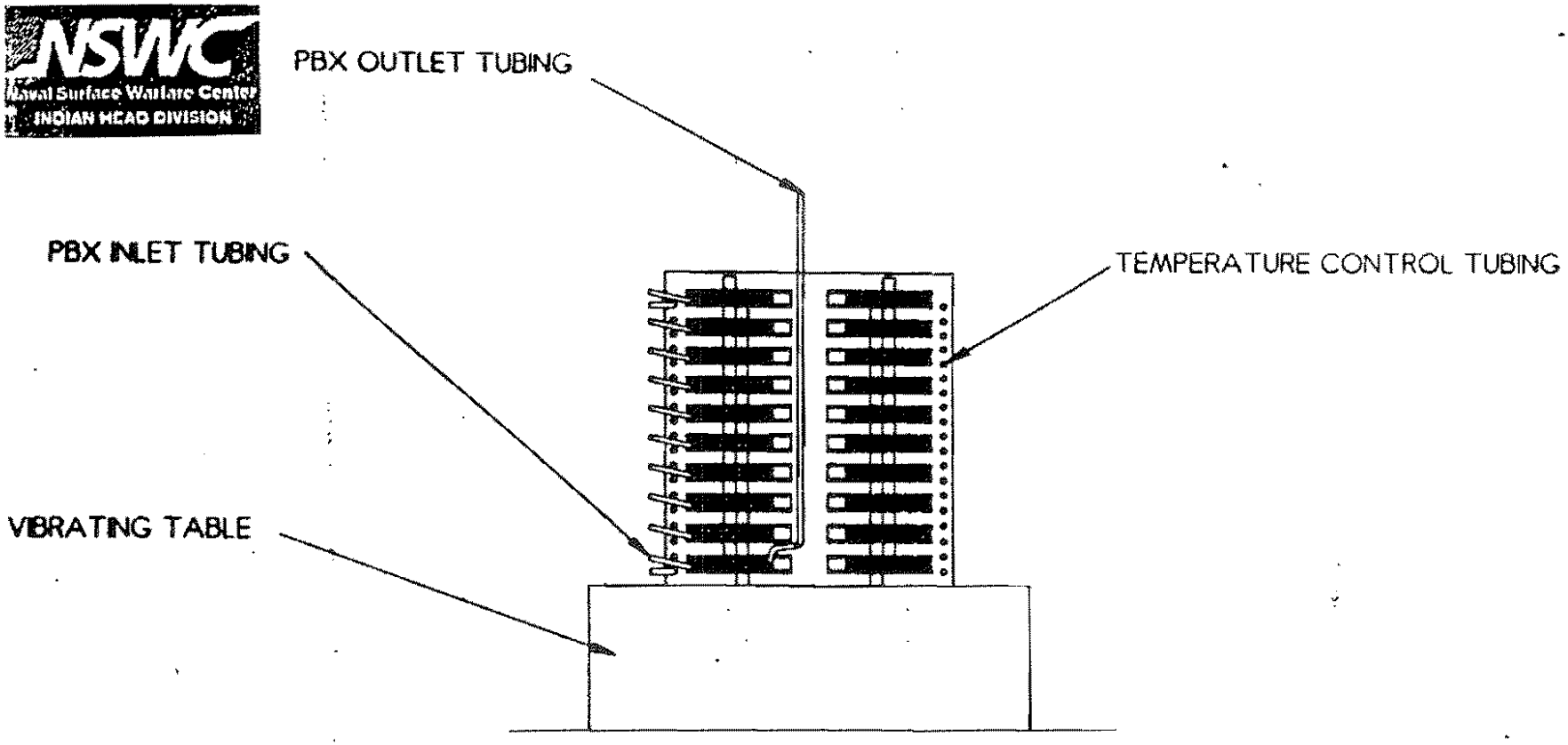

EXPLOSIVE ROPE SPOOL OVEN

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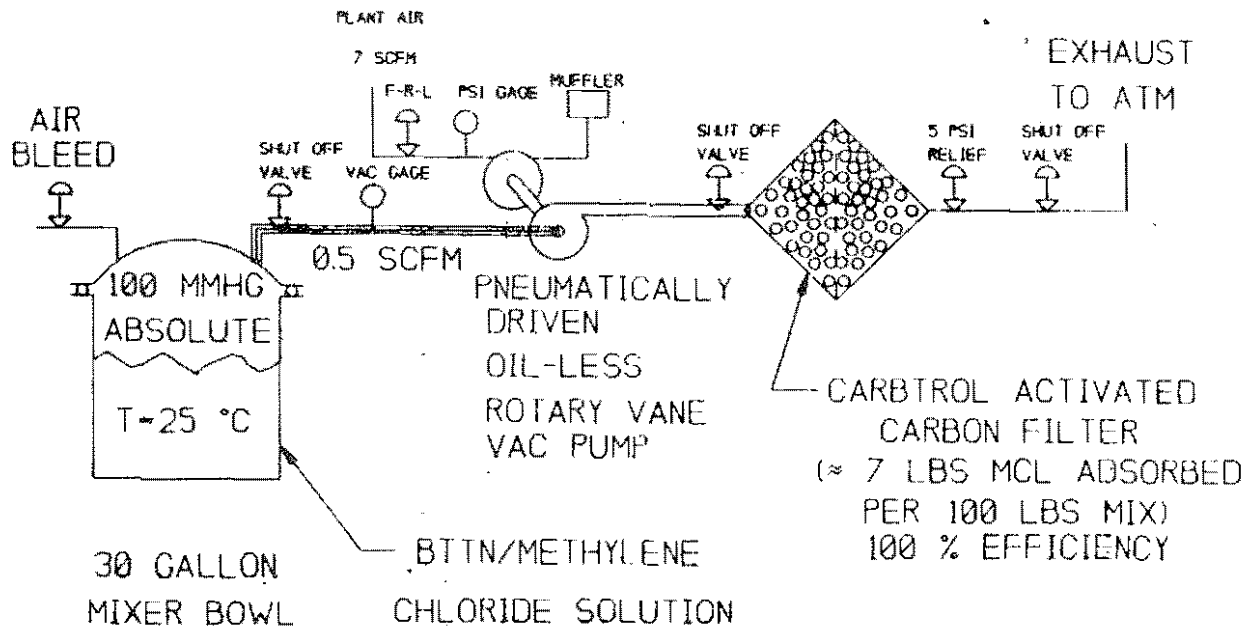
METHYLENE CHLORIDE STRIPPING SYSTEM



COSTS:

OIL-LESS ROTARY VANE VACUUM PUMP	$1000
2 CARBTROL CARBON CANISTER DRUM FILTERS	$1400
PLUMBING, VALVES, GAUGES & FITTINGS	$500
CARBON DISPOSAL	$500
LABOR	$3000
TOTAL	$6400

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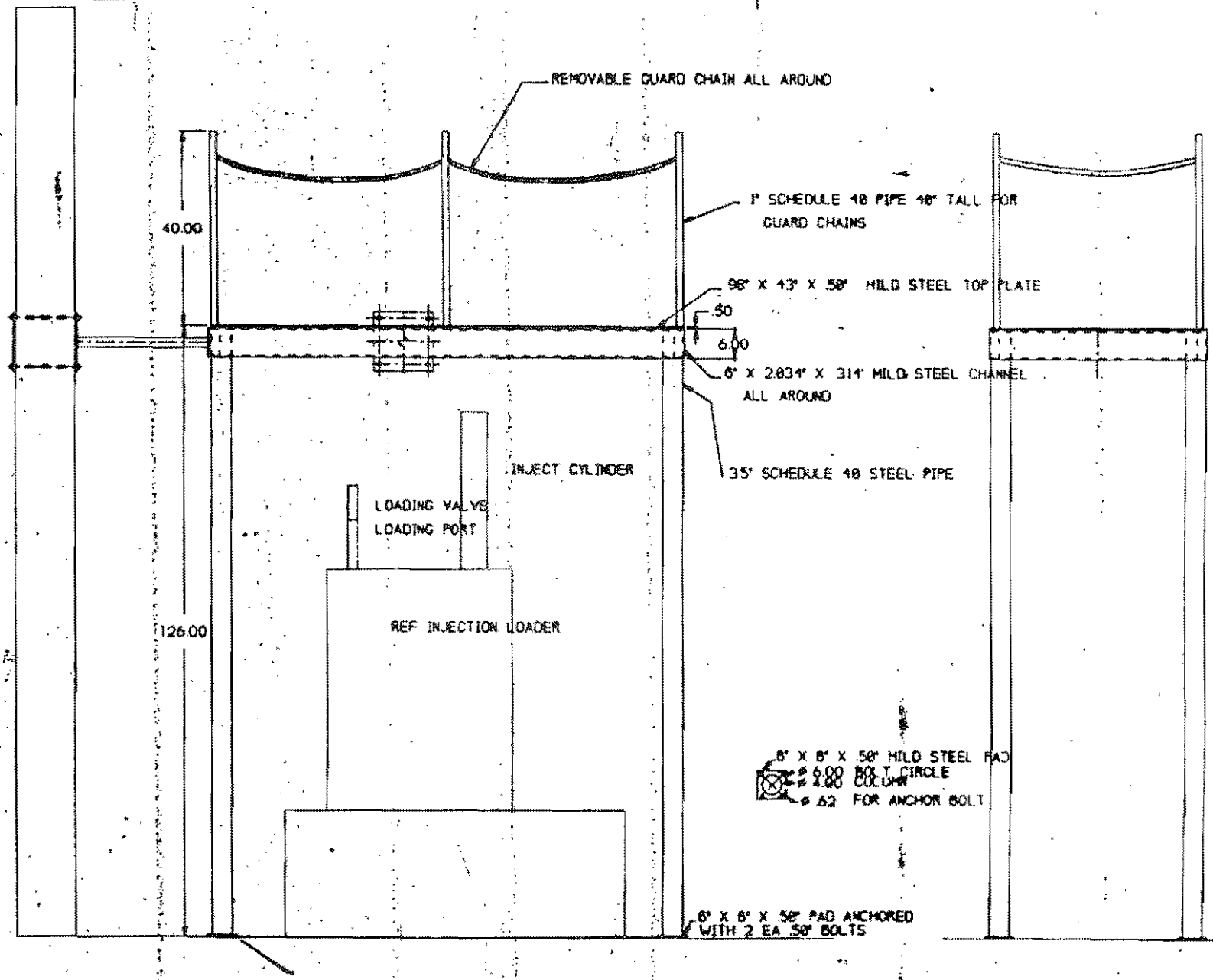

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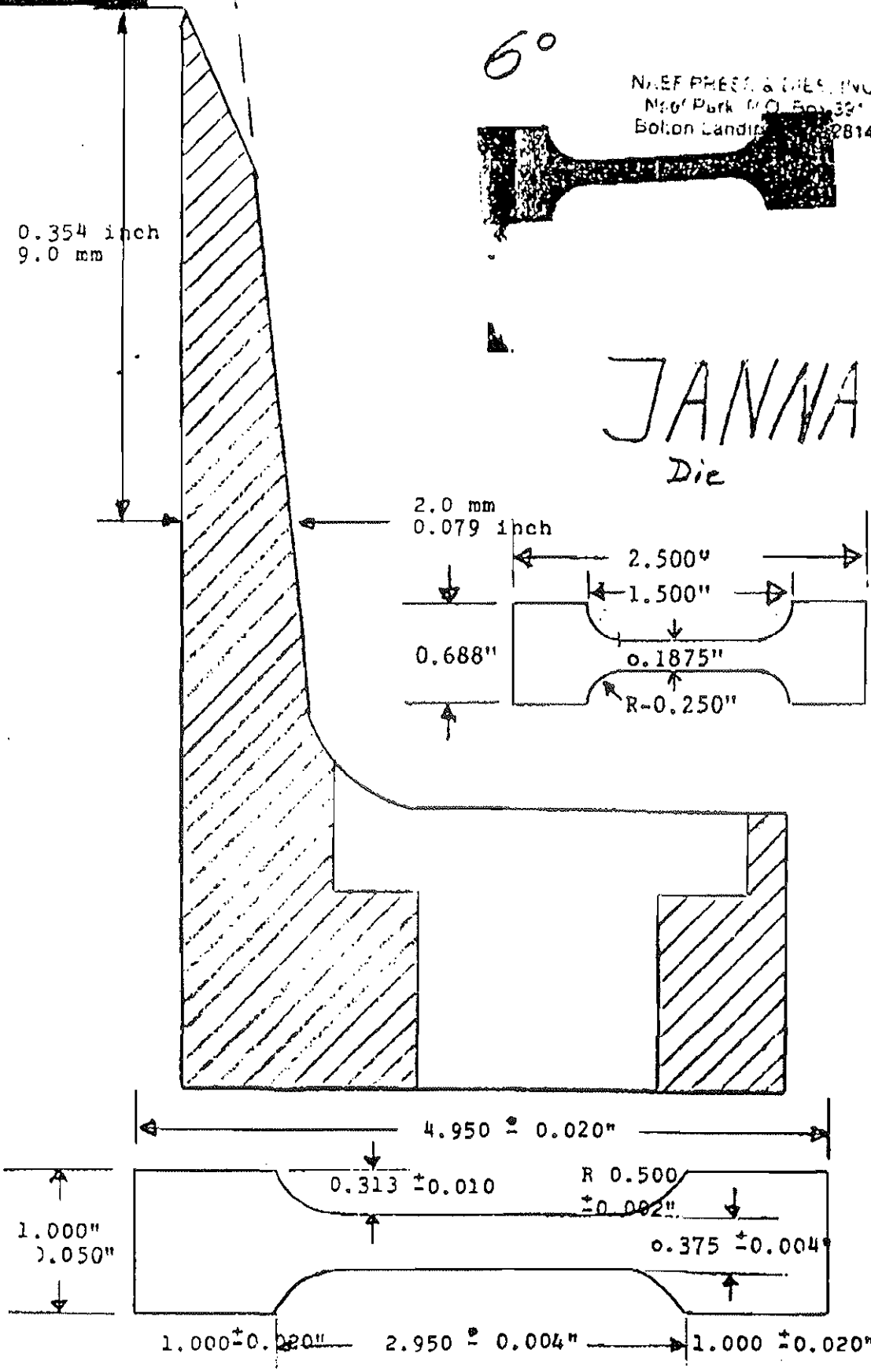
NAEF
Special cutting edge.

6°

JANNAF
Die



Half-Scale JANNAF
Tensile Specimens

Full-Scale JANNAF
Tensile Specimens

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ACCOMPLISHMENTS

Successfully Scaled Up SMX-13 Explosive

Successfully Demonstrated "Tube in a Tube" Load Method

(old method involved stripping support tubing then wrapping with Saran Wrap)

Successfully Loaded Over 1800 Feet Of SMX-13 Detonation Cord

Assisted NSWC WO in setting up SX-2 and SMX-13 arrays for Lethality Tests at Eglin, AFB

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ISSUES

RAW MATERIALS

HMX

Cost $$$
Washing versus Grinding

BTTN

Limited Suppliers
Cost $$$
Shipped in MeCL2

PAO

Melt PAO into Plasticizer to Form Laquer

BATCH & LOAD

Time to Batch and Load is Excessive

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LESSONS *LEARNED*

1. *No ingredient weight % changes were required during scale-up*
2. *Polymer should be broken into small pieces and melted overnight*
3. *Ensure all liquid ingredients are stored under nitrogen*
4. *Use nitrogen when breaking vacuum in the mixer bowl*
5. *60 lbs of BTTN requires a minimum of 4 hours at 52 F and 5 mm HG vacuum to remove MeCl2*
6. *Always dry and screen solids prior to addition*
7. *Cool QA sample to 40 C prior to cutting dog bone*
8. *Blade speeds of 24 to 35 rpm are required to ensure proper mixing*
9. *Vibration and Heat are required to decrease load times*
10. *HMX should have an average particle size of 10 micron with no particles below 1 micron to obtain EOM viscosity suitable for processing*
11. *SMX-13 behaves favorably in our injection loader when subjected to pressures up to 300 psig*

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CONCLUSIONS

Our detachment has successfully batched SMX-13 from 25 grams to 200 lbs

Our SMX-13 mechanical property and senstivity data is comparable to NAWC China Lake's development data

Batching SMX-13 can be accomplished if "lessons learned" precautions are followed

Injection loading into polyethylene tubing is a viable way to load detonation cord if the "tube in a tube" method is used along with heat and vibration

Preliminary data from Lethality Tests indicate that the SMX-13 array out performed the SX-2 array by a significant margin suggesting SMX-13 will replace SX-2

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FUTURE

Investigate reducing batch and load times

Investigate other means of loading to suit production

Load 2000 feet of SMX-13 detonation cord to support ongoing tests

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Status Review of Twin Screw Extruder Facility at LHAAP

by
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ABSTRACT

Thiokol Corporation has been working on continuous processing of energetic materials for many years. Ordnance Operations has developed a pilot facility for processing energetic materials based on a Werner & Pfleiderer ZSK-58E twin-screw extruder. The facility has produced a variety of compositions, including infrared decoy flare compositions, CAB/NC LOVA gun propellant, TPE gun propellant, and CAB explosive compositions with HMX.

This paper will describe the latest work in processing explosives based on CAB binder with an energetic plasticizer and HMX as the nitramine oxidizer. The process utilizes a lacquer of all ingredients except the nitramine. The lacquer is pumped as a liquid into a twin-screw extruder/compounder with the nitramine being fed from a loss-in-weight feeder as a dry powder. The ingredients are compounded, granulated and dried to a free-flowing powder. This process has proven to be effective and low cost. All of the process steps, including granulation, are continuous.

This process is proposed for the Flexible Manufacturing Plant for Energetics now being designed by Thiokol at the Longhorn Army Ammunition Plant. Both RDX and HMX compositions have been successfully produced in the facility.

INTRODUCTION

Processing of energetic materials in conventional production is based on batch processing of compositions which has several disadvantages. Batch processing requires considerable time in mixing to reach a state of homogeneity in the composition. In addition, batch processing means that a large quantity of material is suddenly available at the end of the mix cycle. This requires close attention to pot life and material handling to avoid overloading bays with quantities in excess of quantity-distance criteria. Other batch processing problems include generation of considerable quantities of waste material from cleaning operations at the end of the mix cycle. Safety is a big concern in batch processing because of the quantities of material that must be handled during the process. Safety of personnel and protection of the equipment investment are both very important in the manufacturing of energetic materials. Most batch mixing equipment is limited in the degree of flexibility that can be used in the manufacture of energetic materials. Some products have been shown to be beyond the capability of specific batch mixers, thereby limiting the products that can be produced in a facility.

Continuous processing offers solutions to many of the problems that are inherent in batch processing. In continuous processing, the material is available immediately after mixing at a rate commensurate with processing into items. The operations are remote, lending safety to personnel, and the operations have minimal product in process at any given time so that equipment is subjected to reduced hazard in the event of an unplanned ignition. Since clean-up only occurs at the end of the run and the amount of material in process is minimal, there is considerably less waste product to dispose of at the end of processing. By working with only small amounts of composition in the compounding step, it is possible to increase the amount of work done to the composition and to mix materials that are not processable in normal batch equipment.

Thiokol has had an IR&D project for continuous mixing since 1984. In 1988, a twin-screw extruder was received at the Thiokol Longhorn Division in Marshall, Texas to continue work on continuous processing. Thiokol is the operating contractor of Longhorn Army Ammunition Plant near Marshall, and the twin-screw extruder was used to establish a pilot facility using IR&D and Thiokol capital funds. With this facility, preliminary process development was demonstrated to show the flexibility of the system for processing energetic materials. Live demonstrations with solid rocket propellant were conducted in August, 1989. The propellant produced was tested for physical and ballistic properties and found to meet or exceed all batch performance criteria. After this work, the twin-screw facility produced infrared decoy flare composition to demonstrate flexibility and safety by providing remote operation of the entire process. The use of the twin-screw facility to produce live Low Vulnerability Ammunition (LOVA) gun propellant using a thermoplastic elastomer binder further showed the versatility of the process system. As a result of the IR&D project demonstrations, Thiokol was able to offer the Army Production Base Modernization Activity (PBMA) a proven system on which to design and build a Flexible Manufacturing Plant for Energetics.

Using proven technology approaches, Thiokol has started the design of a Prototype Flexible Manufacturing Plant for Energetics at the Longhorn Army Ammunition Plant. This facility has the advantage of limited production capability of many different energetic items, including solid propellant rocket motors, plastic bonded explosive (PBX) compositions, infrared decoy flares, LOVA gun propellants, CAB/HMX explosives and a variety of pyrotechnic formulations. The application of the Thiokol pilot facility to demonstrate the technology before committing the design of the system is a distinct advantage and lowers the risk to the Army.

Thiokol has continued to apply IR&D and capital funds to continuous process development, including the addition of a continuous dryer and a continuous granulator for some products.

EXPLOSIVE COMPOSITION PROCESSING

Picatinny Arsenal eXplosives (PAX) have been based on use of a cellulose acetate (CAB) binder system with a plasticizer and HMX as the primary oxidizer. Different energetic

plasticizers have been used in these formulations, including DEGDN, TEGDN and BDNPA/F. The current process being developed on the Longhorn Division Pilot Plant utilizes a continuous compounding of ingredients in a totally remote operation. The process produces a PAX type explosive composition in a granulated form suitable for feeding to dies and pressing into warheads. The product is analogous to LX-14 but is less sensitive to external stimuli.

The basis of the system is a Werner & Pfleiderer 58mm twin-screw extruder with the required ancillary support equipment. This is a split barrel design with numerous safety features. The initial system has been reported on in papers presented at the 15th International Pyrotechnic Seminar in 1990, the 24th DoD Explosives Safety Board Seminar in 1991 and the JANNAF Propulsion Meeting in 1993.

The twin-screw extruder in the pilot facility was designed by Werner & Pfleiderer to Thiokol's requirements. Since those papers were presented, processing demonstrations have produced some major improvements.

One of the major advances in continuous processing of these explosives involves the development of a process for the production of a granular composition. The original batch manufacturing process involved using a horizontal sigma-blade mixer to compound the explosive, followed by blocking, billeting and extrusion with chopping to give a granular material. The granules were then dried and used as feedstock in the pressing of warheads. This batch operation is very time consuming and labor intensive, in addition to producing bulk quantities of the material to be handled at one time.

The continuous process involves producing a lacquer of all of the ingredients except the HMX and pumping this lacquer to the extruder while adding the required HMX. After compounding the lacquer and HMX, the excess solvent is stripped in the barrel section with temperature and vacuum down to the 15± 5% range and the product exits the compounder in a coarse granular form. In this case, the twin-screw extruder is operated in a compounding mode without a die. The compounded product can then be conveyed to a continuous granulator for reduction to a uniform particle size and dried to less than 0.1% solvent. The resulting granular material is very free-flowing and homogeneous. The granular feedstock can then be fed to the press for consolidation into warheads.

The granulator used for this process is a Prater Granulator. The granulator uses a cylindrical screen with a non-contact rotor that slings the material through the screen in a continuous stream. The lower discharge port feeds the granulated product to a conveyor that takes it away for drying. In a production mode, the granulated material will be fed to a continuous plate dryer, such as a Krauss Maffei dryer. The Krauss Maffei in use at Longhorn has been tested and shown to be effective in drying solvents from products by conductive heating under mild vacuum as the product moves from tray to tray. The output from the dryer will be sent to a packaging station for packout for shipment to producers. If desirable, the feedstock can be blended to improve homogeneity of a

production lot. It would be feasible to pre-test the composition to assure compositional validity prior to final packout.

The bulk density of the explosive was found to 0.8 gm/cc. The pressed density was 1.78 gm/cc. Both densities were within the desired range for production. As noted in other compounded products, the materials are so uniformly coated that it is difficult to analyze the composition by extraction. An NMR technique was developed to determine the percent of nitramine present in the composition. The analysis confirmed the formulation was within specification. Impact test at Longhorn gave a value of 9 in. for 10% fire with a 4 lb ball. The Thiokol Friction Test for Steel on Steel showed that the product explodes at 43 lb. ESD testing gave a value of 1.0 joules before ignition. These values compare with 5 in. impact, 20 lb friction and 19.4 joules (no fire) for ESD on WC-140 (single base) ball powder.

Product was sent to Iowa AAP for consolidation into warheads for performance testing. The product fed to the dies and consolidated without difficulty. Test data are not currently available on performance but the explosive composition processed well.

CONCLUSIONS

The continuous process has proven very reliable for continuous manufacture of PAX type explosives. Using this approach, the design of a flexible manufacturing plant for energetic materials is progressing with significant improvements in safety and cost of products. The processing cost per pound of explosive is reduced significantly and the quality is improved. The system operates in a closed-loop mode to allow recovery of solvents from the process, thereby making it more environmentally acceptable than batch mixing and tray drying in ovens.

The versatility of the system to produce a variety of energetic materials assures that the plant can be used to manufacture a broad range of products. The environmental aspects being addressed by this project will make the new facility totally compliant with current and future anticipated requirements. Minimization of waste and elimination of emissions are key features in the design. The elimination of obsolescence in the facility results from the broad range of materials that can be produced, including propellants, explosives and pyrotechnics. This approach protects the investment in a manufacturing facility and makes good sense in these days of uncertainty where item viability can change dramatically, almost overnight.

Propellant and Pyrotechnic Formulations Demonstrated

- Composite Rocket Propellant
  - Ammonium perchlorate, aluminum, HTPB, IPDI
  - Loaded ballistic test motors and 70 lb BATES motor
  - Good physical properties and ballistic tests
- Infrared Decoy Flares
  - PTFE, magnesium, Hycar binder - MJU-7, ALA-17, M-206
  - PTFE, magnesium, fluoroelastomer binder - MJU-8
  - Excellent homogeneity and reproducibility of composition
  - Production implementation for M206

Gun Propellant Formulations Demonstrated

- TPE LOVA
  - TPE, RDX, NC, energetic plasticizer, ethyl centralite
  - 110 lbs extruded, chopped and reprocessed three (3) times
  - Final extrusion and testing at Elkton - excellent quality
- Solvent Processed LOVA - M43
  - CAB, NC, RDX, energetic plasticizer, ethyl centralite, LICA-12
  - Compounded and dried feedstock
  - Re-solvated and extruded in 19 perf configuration continuously
  - Good homogeneity (no ballistic firings)

PAX EXPLOSIVE PROCESSING

Fomulation:

- Cellulose acetate butyrate(CAB) binder
- Plasticizers (TEGDN, DEGDN, BDNPA/F)
- HMX (nominal 5 micron)

Compounding:

- 5 micron HMX received from Holston and tray dried
- All other ingredients dissolved in ethyl acetate solvent
- HMX fed with Control & Metering twin-screw loss-in-weight feeder
- Lacquer pumped with gear pump controlled by mass flow meter
- Compounding and solvent reduction in twin-screw extruder
- Coarse granules conveyed to Prater Continuous Granulator for particle size control
- Product dried and packed in fiber drums for shipping

PAX EXPLOSIVE PROCESSING

Other process advantages:

- **Remote, continuous drying for production**
- **Product may be surged, allowing verification of performance before further processing**

CONCLUSIONS

- The continuous process has been demonstrated for continuous manufacture of PAX explosives.
- The design of a flexible manufacturing plant for energetic materials is progressing with significant improvements in safety and cost of products.
- The versatility of the system to produce a variety of energetic materials has been demonstrated.
- The process will be totally compliant with current and future anticipated environmental requirements. Minimization of waste and elimination of emissions are key features in the design.
- Flexibility of processing results in elimination of obsolescence of the facility.

Gun Propellants of the Future Processable via TSE ??

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Continuous Mixer & Extruder Users Group Meeting
Indian Head, MD

20-22 September 1995

Selected Ingredients of Interest

Polymers	Plasticizers	Solids
NC - various %N	ATEC	RDX
CAB	DOA	HMX
CA	DOS	TAGN
ETCEL	BDNPA/F	DATH
HTPB	GAP	DADNH
HTPE	DANPE	CL-20
GAP	DDDD	TNAZ
AMMO	MeNENA	NTO
BAMO	EtNENA	ADN
NIMMO	BuNENA	AN
PVN	TMETN	
PGN	TEGDN	
	BTTN	
	NG	

TSE Propellants of the Future

- May be dramatically different than current ones
  - higher plasticizer/polymer ratios
  - drastically different rheologies
  - zero to very high volumetric solids loading

- Some will use volatile solvent ... some will not
  - Shear roll mill ---> homogeneous input

- Some may be minor variations of current single- and double-base
  - Essentially all polymeric binder ... very little plasticizer

- Some may be more like solventless double-base JA-2
  - Exceedingly tough "viscous" binder

- Some plasticizers are better than others
  - Unpredictable swell at die face

- TPE binders require higher temperature than conventional

TSE Propellants of the Future
(continued)

- Solid loadings may be higher than 70-75% volume

- Bimodal ... or trimodal packings are likely
    - 2μ + 20μ + 200μ (or wider)

- Coarse solids >100μ likely to be broken into smaller fragments
    - Need to prevent breakage to retain proper packing sizes

- Coarse solids >100μ difficult to retain in extruded strands
    - Will be ejected from the surface ... leaving pits + voids

XM-39 vs M43 Gun Propellant

- Differ only in ATEC vs BDNPA/F plasticizer
- Batch process + ram extrusion ... no difference
- TSE process ... substantial difference in rheology
- Problem = If this subtle change caused such a dramatic effect
    - What will major changes do ??
- Need to anticipate rheology changes ... especially dramatic ones

Potential of 21st Century Propellants

	10% GAP 15% MeNENA 75% RDX	30% DANPE 70% DATH	16% BAMO 84% CL-20
Impetus - joules/g	1355	1460	1417
Tv - °K	3635	3641	4200
Gas MW	22.3	20.7	24.7
Gamma	1.245	1.268	1.245
Qex - cal/g	1173	1576	1248

Potential of 21st Century Propellants
(Continued)

	50% MeNENA 50% DANPE	30% DANPE 70% TNAZ	16% BAMO 84% RDX
Impetus - joules/g	1313	1487	1377
Tv - °K	2978	4086	3639
Gas MW	18.9	22.8	22.0
Gamma	1.274	1.246	1.252
Qex - cal/g	909	1287	1137

SCALE-UP

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• When developing some industrial process, initial testing must be done on euipment of smaller scale than that for the production.

• Once the process is developed, it must be scaled up to be at production sized machines (e.g. tests may be done on 2" diameter extruders and then run on 6" diameter extruders).

• In order to do scale-up - must know the processes occuring which as we have studied before are:

Melting	**Pumping & Mixing**

• These processes do not have the same scale-up rule.

Important Parameters for Scale-up

Geometrical Parameters

- Diameter (D)
- Channel Width (W)
- Channel Height (H)

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Important Parameters (cont..)

Operating Parameters

- Screw Speed (N)
- Melt Output Rate ($Q = Q_D + Q_P$)
- Shear Rate $\dot{\gamma} = \pi DN/H$
- Circumferential Speed (V_b)
- Residence Time $t = L/V_0 \sim L/\pi DN$

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Important Variables

- Solids Conveying Rate $\dot{M}_s = \rho H p W V_b \left(\cos\phi - \frac{\sin\phi}{\tan(\theta+\phi)} \right)$
- Melt Conveying Rate $\dot{M}_P = \left(\frac{\rho_m K_m V_b \sin\phi \Delta T_b F_1 l k \delta}{\Delta H} \right)^{\frac{1}{2}} \Delta Z \sqrt{W_s}$
- Screw Power $Z = A\tau V_b$ (shear stress on the barrel A to move fluid V_b)
- Specific Energy Consumption $\left(\hat{Z}\right)$

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Scale-up for Specific Processes

- Shear Rate (Pumping)

$$\dot{\gamma} \approx \text{constant}$$

$$\text{by } H \approx D,\ N \approx \frac{1}{\sqrt{D}}$$

- Heat Transfer (to keep same temperature profile)

$$\text{Graetz Number} = \frac{VH^2}{\alpha L} = \frac{\text{flow rate}}{\text{heat transfer rate}}$$

$$\text{Brinkman Number} = \frac{\eta V^2}{k\Delta T} = \frac{\text{viscous heat}}{\text{conduction}}$$

- Mixing

$$\dot{\gamma} = \text{constant} = \frac{\pi DN}{H}$$

$$t = \text{residence time} = \text{constant} = \frac{L}{V} = \frac{L}{\pi DN}$$

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Let's see what each approach gives and how it is developed:

Constant Shear Rate:

Here, $\phi \approx$ constant, $W \approx D$, $H \approx \sqrt{D}$, $N \approx \frac{1}{\sqrt{D}}$

$$\therefore \dot{\gamma} = \frac{\pi DN}{H} \approx \frac{D \bullet \frac{1}{\sqrt{D}}}{\sqrt{D}} \approx D^0$$

Drag Flow – Q_D

$$Q_D = \left(\frac{4+n}{10}\right) pWH\pi DN \cos\phi$$

where, p = number of flights

$$Q_D \approx WHDN \text{ as } \left(\frac{4+n}{10}\right)\cos\phi = \text{constant}$$

$$\frac{Q_{D2}}{Q_{D1}} = \left(\frac{D_2}{D_1}\right)\left(\frac{D_2}{D_1}\right)^{\frac{1}{2}}\left(\frac{D_2}{D_1}\right)\left(\frac{D_1}{D_2}\right)^{\frac{1}{2}} = \left(\frac{D_2}{D_1}\right)^2$$

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Melt Capacity - what happens to the rate of melting

$$\dot{M}_P = \left(\frac{\rho_m K_m V_b \sin\phi \Delta T_b F_1 K_2}{\Delta H} \right)^{0.5} \Delta Z \sqrt{W_s}$$

$$\frac{\dot{M}_{P2}}{\dot{M}_{P1}} = \left(\frac{V_{b2}}{V_{b1}} \right)^{0.5} \frac{\Delta Z_2}{\Delta Z_1} \left(\frac{W_{S2}}{W_{S1}} \right)^{0.5}$$

$$V_b \approx \pi N D \approx \frac{1}{\sqrt{D}} D \approx \sqrt{D}$$

$$\frac{\Delta Z_2}{\Delta Z_1} \approx \left(\frac{D_2}{D_1} \right)^{0.5} \text{ and } W_{S2} \approx D$$

$$\therefore \frac{\dot{M}_{P2}}{\dot{M}_{P1}} \approx \left(\frac{D_2}{D_1} \right)^{0.25} \left(\frac{D_2}{D_1} \right)^{0.5} \left(\frac{D_2}{D_1} \right)^{0.5} \approx \left(\frac{D_2}{D_1} \right)^{1.25}$$

But,

$$\frac{Q_{D2}}{Q_{D1}} \approx \left(\frac{D_2}{D_1} \right)^{2}$$

Hence, it does not keep up with the increase in the flow rate.

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Scale-up for Mixing

2 - Rules

$$\dot{\gamma} = \frac{\pi DN}{H} = \text{constant}$$

$$t = \frac{L}{\pi DN} = \text{constant}$$

if L / D is constant,

N must be constant - from (2)

$\therefore$ H = D - from (1)

Disadvantages

- Output higher than melt capacity

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Scale up for Heat Transfer

$$\text{Graetz Number} = \frac{VH^2}{\alpha L} \qquad (1)$$

$$\text{Brinkman Number} = \frac{\eta V^2}{k\Delta T} \qquad (2)$$

Considering $V = \pi DN$ and L / D = constant,

Equation (1) becomes,

$$NH^2 = \text{constant}$$

Equation (2) becomes,

$$V = \text{Circumferential Speed} = \text{constant}$$

$$\therefore\ N \approx 1 / D$$

Putting this into equation (1) gives,

$$H \approx \sqrt{D}$$

Good agreement - fit for pump, melt, conveying rates & spec. energy consumption.

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Scale-up Factors

	Pump	HT-X	Mix
• Diameter (D)	D	D	D
• Channel Width (W)	D	D	D
• Channel Depth (H)	$D^{0.5}$	$D^{0.5}$	D
• Screw Speed (N)	$D^{0.5}$	D	D^{0}
• Melt Output Rate (Q_P, Q_D)	D^{2}	$D^{1.5}$	D^{3}
• Shear Rate ($\dot{\gamma} = \frac{\pi DN}{H}$)	D^{0}	$D^{0.5}$	D^{0}

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Scale-up Factors (cont..)

	Pumping	HT-X	Mixing
• Circumferential Speed $(V_b = \pi N D_b)$	$D^{0.5}$	D^0	D
• Residence Time $\left(t = \frac{L}{\pi N D}\right)$	$D^{0.5}$	D	D^0
• Melt Capacity $\left(\dot{M}_P = \left(\frac{\rho_m K_m V_b \sin\phi \Delta T_b F_1 K_2}{\Delta H}\right)^{0.5} \Delta Z \sqrt{W_s}\right)$	$D^{1.75}$	$D^{1.5}$	D^2
• Solids Conveying $\left(\dot{M}_s = \rho H p W V_b \left(\cos\phi - \frac{\sin\phi}{\tan(\theta+\phi)}\right)\right)$	D^2	$D^{1.5}$	D^3
• Screw Power $(Z = A\tau V_b)$	$D^{2.5}$	$D^{1.5}$	D^3
• Specific Energy Consumption $\left(\hat{Z} = \frac{Z}{Q_T}\right)$	$D^{0.5}$	D^0	D^0

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Scale-up Revisited for Partially Filled Twin Screw Extruders

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Objective

Determine appropriate scale-up rules for distributive mixing in partially-filled channels.
By using the experimental method to find out how the factors below effect mixing length:

* screw angular velocity - rpm
* Percentage of channel filled
* Diameter of screw
* Stagger
* Interactions of these main factors

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TRADITIONAL SCALE UP METHODS FOR MIXING

It is assumed that the two most important parameter in mixing are:

STRAIN RATE: $$\dot{\gamma} = \frac{\pi ND}{H}$$

RESIDENCE TIME: $$t = \frac{L}{\pi NDcos\,\theta\,\sin\theta}$$

the scale-up rule is derived by keeping these two parameters constant that is, if L/D is constant, the factors for mixing:

$$N = \text{constant}$$

$$H \approx D$$

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RESULTS PREDICTED BY STANDARD SCALE -UP RULES I

	Small Extruder	Large Extruder			
		H~S		H~$\sqrt{S}$	
	value	equation	value	equation	value
Diameter	d=0.8	D=d*S	2.0	D=d*S	2.0
Channel depth	h=0.1	H=h*S	0.25	H=h*S^{0}	0.158
Screw speed	n=20	N=n*S^{0}	20	N=n*S^{0}	20
Output rate(/ min)	q=1.533	Q=q*S^{3}	23.95	Q=q*S^{3}	15.15
Shear rate	γ = 8.378	$\gamma=\gamma * S^{0}$	8.378	$\gamma=\gamma * S^{0.5}$	13.25
Circumferential speed	v= 0.837	V=v*S^{1}	2.094	V=v*S^{1}	2.094
Residence time	t= 31.2	T=t*S^{0}	31.2	T=t*S^{0}	31.2

* D/d=S

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RESULTS PREDICTED BY STANDARD SCALE -UP RULES II

	Small Extruder		Large Extruder H~S at 40% fill		
	value	equation	value	value	value
Diameter	d=0.8	D=d*S	2.0	2.0	2.0
Channel depth	h=0.1	H=h*S	0.158	0.25	0.25
Screw speed	n=20	$N=n*S^{0}$	10	15	20
Output rate(/min)	q=1.533	$Q=q*S^{3}$	11.98	17.96	23.95
Shear rate	γ =8.378	$\gamma=\gamma*S^{0}$	4.19	6.28	8.378
Circumferential speed	v= 0.837	$V=v*S^{1}$	1.05	1.57	2.094
Residence time	t= 31.2	$T=t*S^{0}$	62.4	46.8	31.2

* D/d=S

*Screw angular velocity will effect mixing length

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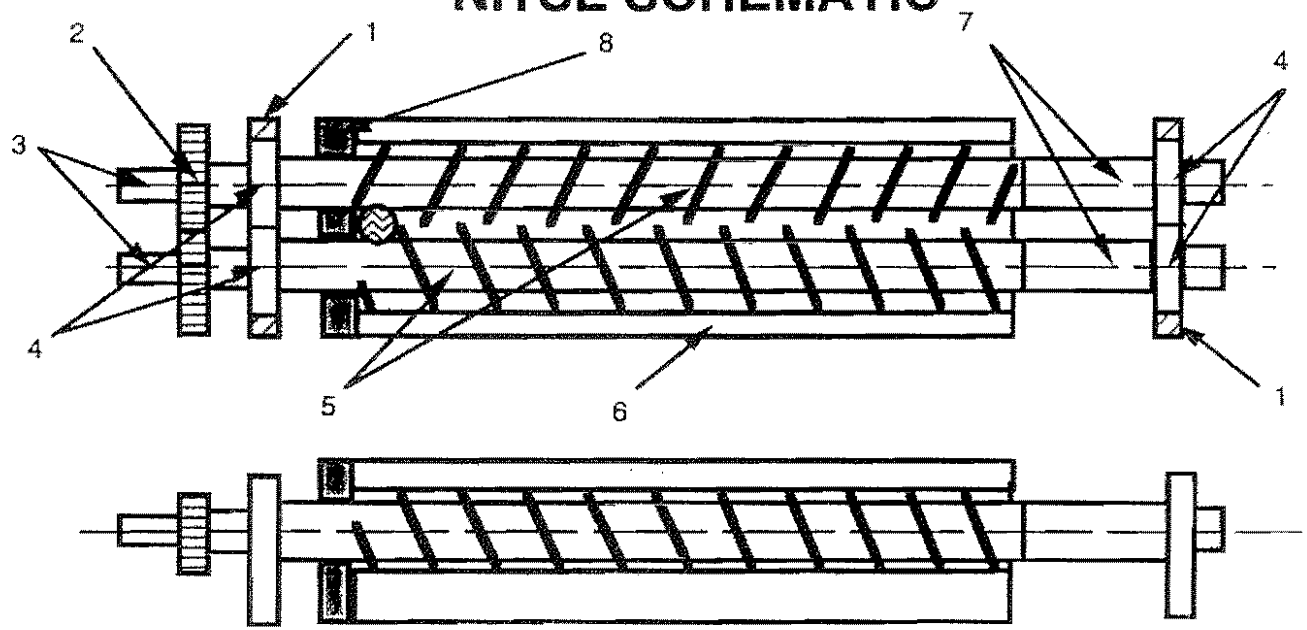
NITSE SCHEMATIC



1. SUPPORT
2. GEARS
3. COUPLES
4. BEARINGS
5. SCREWS
6. BARREL

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EXPERIMENT ARRANGEMENT

* Considering:

    ** Main factors:

        ** Interaction of main factors:

    * Do the experiments

  * Analysis data, set up experic mixing equation .

  * Replicate the experiments

* Compare the results with standard methods.

  * Interpretation of main effects and interactions

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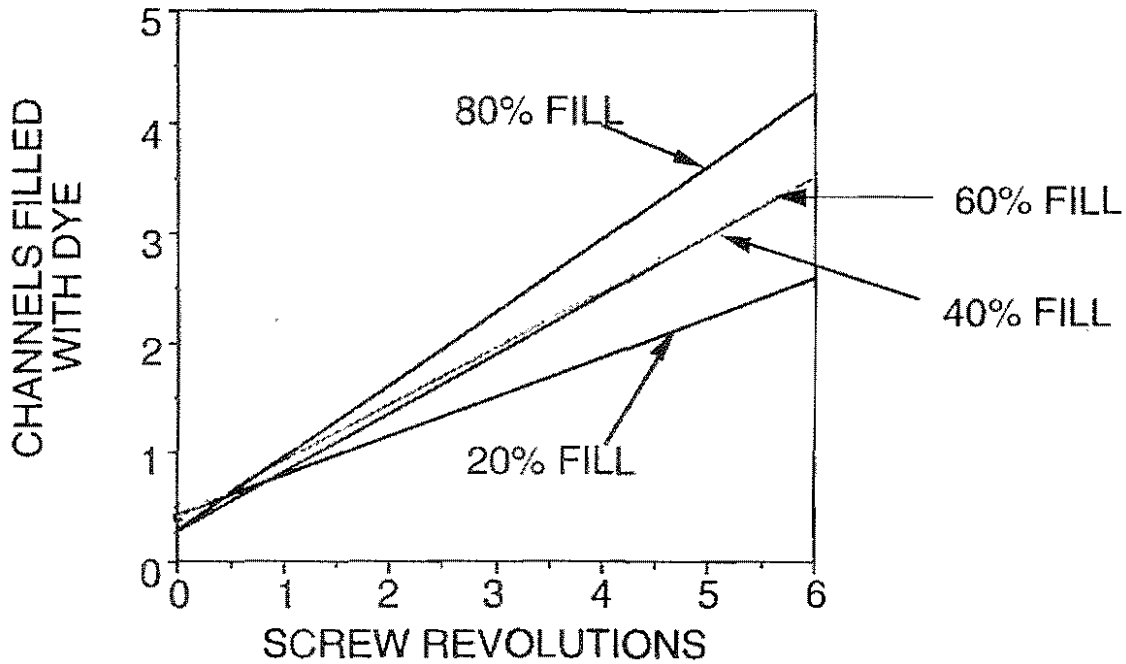
DISTRIBUTIVE MIXING IN 0.8" DIAMETER NITSE

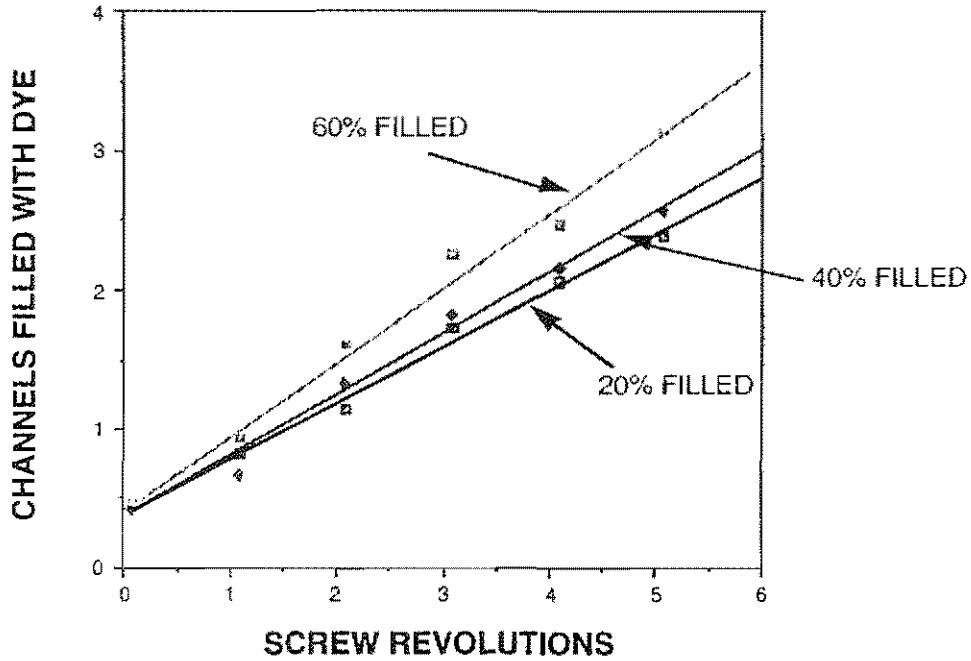
CHANNELS FILLED WITH DYE VS. SCREW REVOLUTIONS FOR 20%, 40%, 60%, 80% FILL AT 25% STAGGER



EXTRUSION DIVISION

DISTRIBUTIVE MIXING IN 2" DIAMETER NITSE

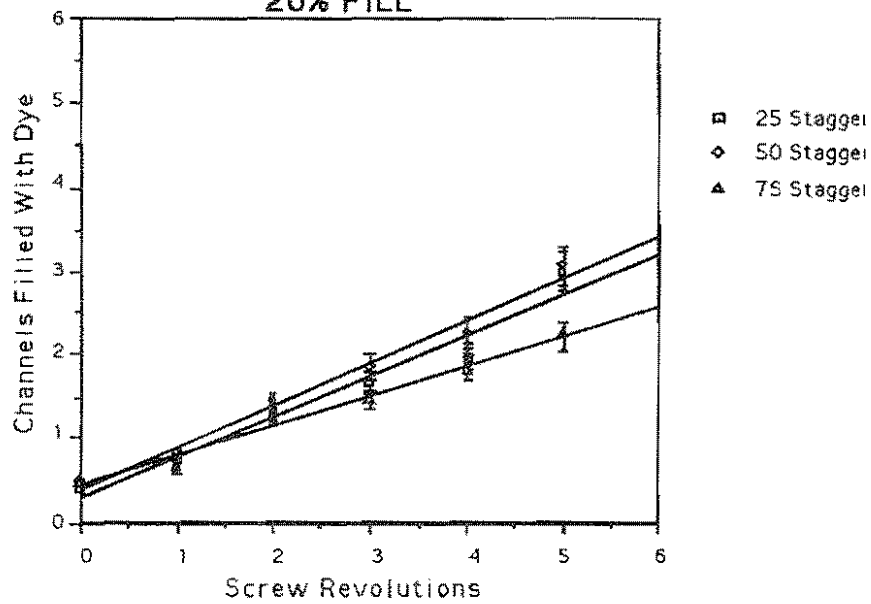
CHANNELS FILLED WITH DYE VS. SCREW REVOLUTIONS FOR 20%, 40%, 60% FILL AT 50% STAGGER,15RPM



EXTRUSION DIVISION

DISTRIBUTIVE MIXING IN 0.8" DIAMETER NITSE

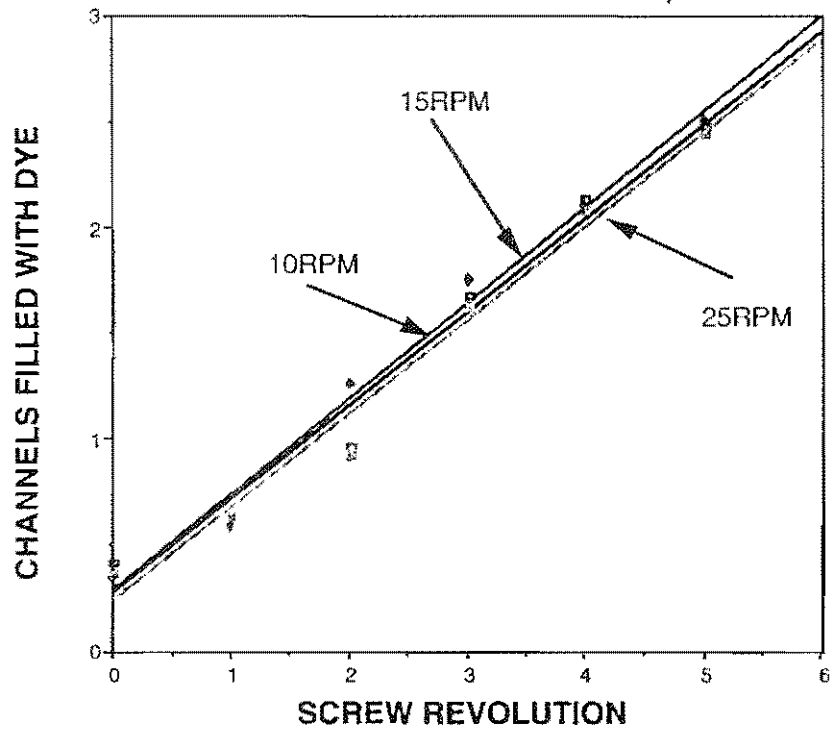
CHANNELS FILLED WITH DYE vs SCREW REVOLUTIONS FOR 25%, 50%, 75% STAGGER AT 20% FILL



EXTRUSION DIVISION

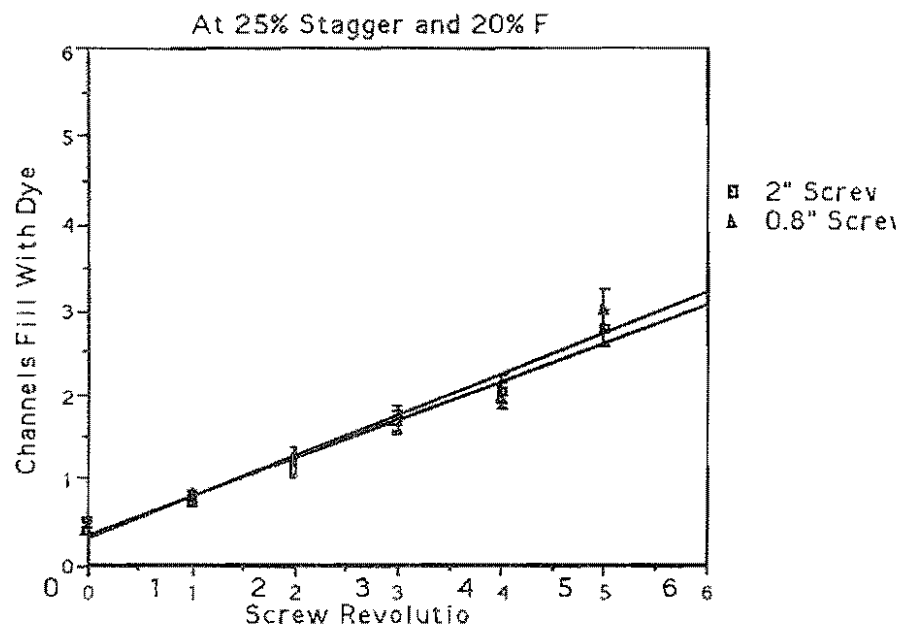
DISTRIBUTIVE MIXING IN 2" DIAMETER NITSE

CHANNELS FILLED WITH DYE VS SCREW REVOLUTIONS FOR 10RPM,15RPM, 25RPM AT 50% STAGGER, 40%FILL



EXTRUSION DIVISION

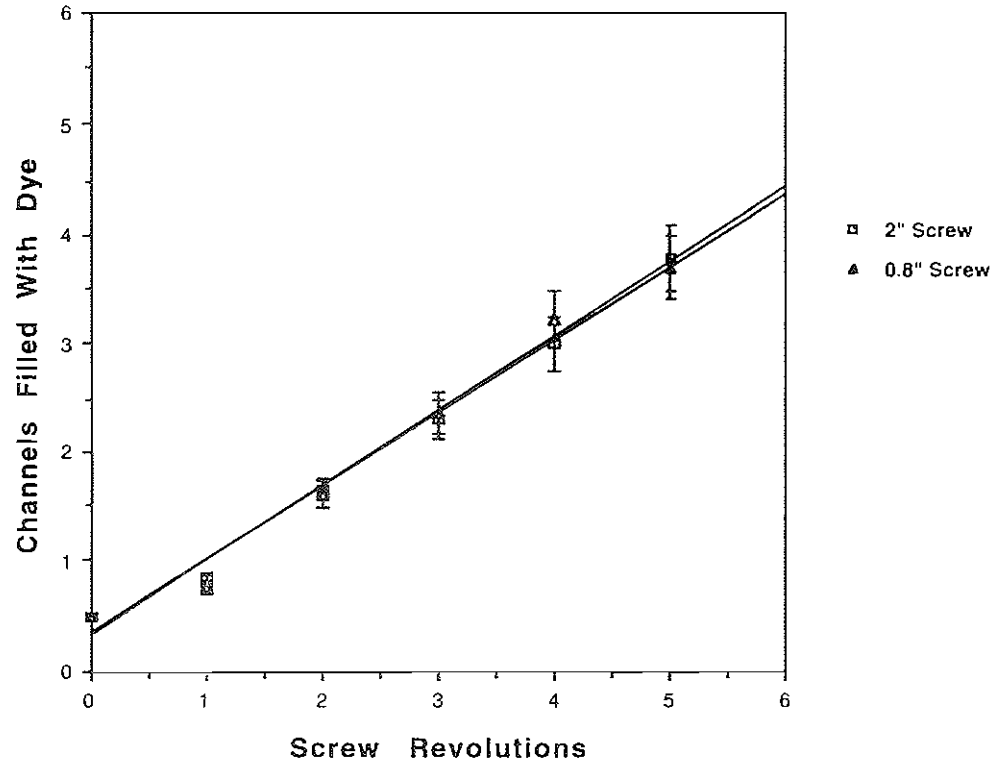
Channels Filled With Dye vs. Screw Revolutions (Diameter Effect)



EXTRUSION DIVISION

Channels Filled With Dye vs. Screw Revolutions (Diameter Effect)

50% Stagger and 40% Fill



EXTRUSION DIVISION

EFFECT OF STAGGER, PERCENT FILLED, RPM, DIAMETER AND THEIR INTERACTIONS

STAGGER EFFECT S = 0.407

RPM EFFECT R = -0.015

PERCENT FILL EFFECT P = 0.426

DIAMETER OF SCREW D = -0.333

S * P INTERACTION = 0.121

S * D INTERACTION = -0.139

P * D INTERACTION = -0.144

EXPERIC MODEL:

$$\text{Yield} = 3.227 + 0.407S - 0.015R + 0.426P - 0.333D + 0.121S*P - 0.139S*D - 0.1447P*D$$

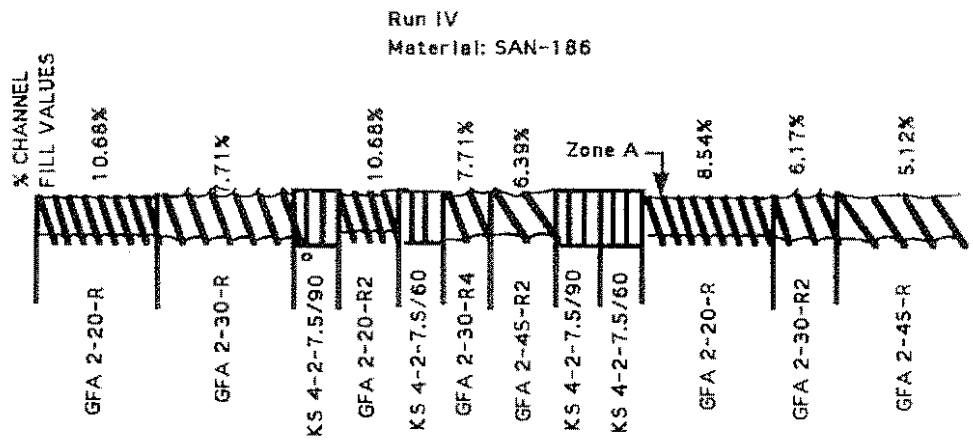
EXTRUSION DIVISION

SCALE UP METHODS FOR MIXING

Former Rules	Our Rules
Shear Rate: $\dot{\gamma} = \frac{\pi ND}{H} = \text{constant}$ Residence Time: $t = \frac{L/\sin\theta}{\pi ND} = \text{constant}$	Total Shear: $S = \frac{L}{H\sin\theta} = \text{constant}$
Applied Condition: $N = \text{constant}$ $\frac{L}{D} = \text{constant}$ $\frac{H}{D} = \text{constant}$	Applied Condition: $\frac{L}{D} = \text{constant}$ $\frac{H}{D} = \text{constant}$

EXTRUSION DIVISION

Case Study

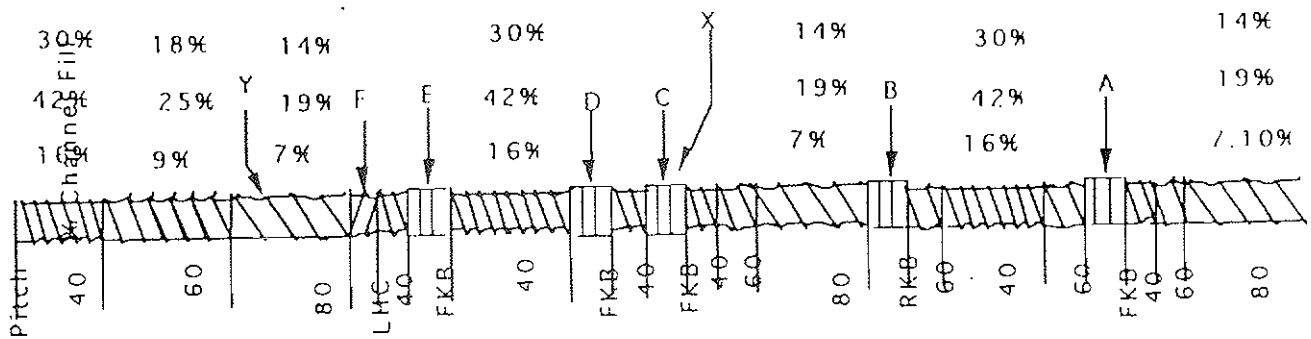


EXTRUSION DIVISION

Case Study

W & P SCREW CONFIGURA

58 mm CoTSI



- First row - channel fill values with scale up rule in indutrial practice
- Second row - channel fill with scale up for Mixing
- Third row - channel fill with scale up for Heat Transfer

EXTRUSION DIVISION

Calibration of CAMES™ Sensors - Technical Update

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Abstract
Improvements have been made in the shear stress calibration of CAlibrated MicroEncapsulated Sensors, CAMES™. A thorough performance evaluation of the calibration instrument, a Sieglaff-McKelvey capillary rheometer, has yielded greater accuracy and reproducibility of on-line shear stress and shear rate data. Anomalous shear rate readings for the calibrating fluid have resulted in original observations of dilatancy in this fluid, a more accurate model of viscous flow in the capillary and improved shear stress calibrations. The development of a new single particle counting technique, using digital signal processing, has validated our percent rupture calibration method by classifying the types of events seen by the on-line microphotometer. Finally, the cumulative effect of these improvements has resulted in confirming previous calibration data and developing a more powerful set of calibration parameters that we now use to specify these materials.

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This paper was presented at the 8th Annual Continuous Mixer and Extruder Users' Group Meeting, Alexandria, VA, 20-22 September 1995.

Calibration of CAMES™ Sensors - Technical Update

Introduction

The concept of sensing shearing forces using microcapsules was patented nearly three decades ago. Here, microcapsules were proposed for measuring "distributed forces" [1] or simply a means for obtaining a copy or record of a pressure event such as writing or typing [2]. A definitive, absolute calibration using fundamental concepts was not performed in either case. Instead, relative calibration of large collections of particles was attempted. Consequently, only rough quantitation was permitted, i.e. low, medium and high pressures.

The use of microencapsulated dye particles, freely supported in a fluid matrix, to detect shear stresses associated with fluid processing techniques was recently demonstrated [3]. Marketed as CAMES™ (CAlibrated MicroEncapsulated Sensors), 40 to 150 μm diameter polymeric microcapsules, with an organic dye-containing core liquid, were shown to rupture in a shear stress field. If the CAMES™ were uniformly distributed in a fluid matrix the pattern of rupture was an indication of the shear stress profile. Thus, CAMES™ were an optomechanical sensor for shearing stress. Mixing phenomena generate shearing stress. Recall that viscosity is the ratio of shear stress to rate of shear, so, at constant viscosity and known rate of shear, extent of microcapsule rupture should be proportional to shear stress. The ability to measure shearing stress in industrial mixers and extruders was the impetus to continued research and development of CAMES™ optomechanical sensors [4, 5].

The rupture of microencapsulated dye particles was monitored in a capillary rheometer, which produced a known shear stress field in the capillary [5]. Poiseuille flow in a cylindrical capillary produces a laminar flow profile with maximum shear rate and maximum shear stress at the wall-fluid interface. Dye-filled microcapsules experience this shear stress field and may rupture,

depending on the field or stress gradient that is superimposed across the particle's diameter. On-line microphotometry records optical absorbance of the capillary contents as a function of time. The dye concentration is measured using optical absorbance. Fluid containing intact microcapsules generates a smaller absorbance signal than the same fluid that contains ruptured microcapsules because the highly localized dye in intact microcapsules attenuate only a small fraction of the light beam. Distinguishing between rupture and nonrupture events allowed computation of rupture extent (%). Plots of % rupture versus shear stress served to calibrate the microcapsule rupture response, thus enabling the CAMES™ designation.

Experimental

Microcapsule Preparation and Characterization

Microcapsules containing a 10 % (w/w) Automate Red B (10 % (w/w) methyl red in xylene) - xylene core liquid were prepared via oil-in-water emulsion polymerization [5]. The polymer wall consisted of an extensively crosslinked urea-formaldehyde-melamine condensation polymer. The microcapsules were classified into the following size ranges: 44-53, 53-63, 63-74, 74-90 and 90-106 µm diameter, using wire mesh sieves (Gilson Co., Inc., Worthington, OH). A proprietary wet sieving technique allowed continuous sieving without microcapsule rupture or sieve blinding.

Fine particle analysis techniques were used to characterize the microcapsules. Wall thickness was measured by scanning electron microscopy of microtomed, epoxy-cast microcapsules. Particle size distributions of each of the classified fractions was obtained by a Microtrac light scattering apparatus. Periodic light microscopy was performed on the classified microcapsules to verify wall integrity and maintenance of the core liquid.

Rupture Response Calibration Instrumentation

A model R-64 Sieglaff-McKelvey capillary rheometer (Tinius Olsen, Willow Grove, PA) was used to generate Poiseuille flow in a capillary that had been fitted with a unique microphotometer.

Figure 1 shows a schematic of the on-line microphotometer. A 6.8 cm long stainless steel capillary with an inner diameter of 0.65 mm was fastened into a standard rheometer die. A pair of ball lenses (Edmund Scientific, Barrington, NJ) were attached to matched and aligned milled openings in the tube wall, approximately 3 cm from the inlet end. Both the capillary/die and ball lens/capillary bonds were made with 353ND epoxy (Epo Tech, Billerica, MA). A physical separation of not less than 0.6 mm, or 80% of the lumen diameter, was maintained between the ball lenses in the observation region of the capillary. This distance, 0.6 mm, was the effective optical pathlength of the transmission photometric configuration. Much of the remaining components and design were based on an LED photometer reported by Dasgupta and co-workers [6]. A silicon photocell (Electronic Goldmine, Phoenix, AZ) was coupled to one ball lens and a high output, green LED (light emitting diode) (Stanley, Dallas, TX).was coupled to the other ball lens. An identical silicon photocell was attached to the base of the green LED using optical epoxy (302, Epo Tech, Billerica, MA). The sample and source photocells were electrically connected to a log ratio amplifier (757N, Analog Devices, Norwood, MA), operated in the current mode. Heavily shielded, long (> 1 m) cables were required for this connection. The source LED was driven with 50 mA at 5 V. The output from the log ratio amplifier was buffered with a voltage follower amplifier (ECG 858M, Sylvania Electronic Products, Williamsport, PA). The conditioned output was displayed on a digital panel meter (DPM-65, Acculex, Taunton, MA) and a strip chart recorder. The microphotometer output calibration was 1.0 AU (absorbance units) per volt. The capillary rheometer outputs of load and velocity were monitored on the provided two-channel chart recorder.

Rupture Response Calibrating Fluid

An optically-transparent, viscous fluid was used to generate a shear stress field in the capillary. This proprietary fluid (CF 232, MACH I, King of Prussia, PA) was carefully chosen for its high viscosity (~ 100,000 mPa·s (cP) at 30 C), excellent optical transparency and extremely high tack (adhesion) to the microcapsules. These features enabled high shear stress to be generated at the

depending on the field or stress gradient that is superimposed across the particle's diameter. On-line microphotometry records optical absorbance of the capillary contents as a function of time. The dye concentration is measured using optical absorbance. Fluid containing intact microcapsules generates a smaller absorbance signal than the same fluid that contains ruptured microcapsules because the highly localized dye in intact microcapsules attenuate only a small fraction of the light beam. Distinguishing between rupture and nonrupture events allowed computation of rupture extent (%). Plots of % rupture versus shear stress served to calibrate the microcapsule rupture response, thus enabling the CAMES™ designation.

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capillary wall and, thereby, on the microcapsules. Using the calibrated load channel output, the capillary dimensions and the calibrating fluid viscosity, shear stress from 20 to 600 kPa could be generated. The shear stress dependent viscosity and the temperature coefficient of viscosity were determined with the Sieglaff-McKelvey capillary rheometer and a Brookfield M81 cone and plate viscometer (Brookfield Instruments, Raritan, NJ), respectively.

Particle Counting and Analysis Instrumentation

Strip chart recordings were scanned with a hand-held scanner (Scanman, Logitech, Los Angeles, CA) using the supplied FotoTouch software. Occasionally, the captured grid was removed with the image editing software. Next, the scanned images were converted to X-Y data files with Unscanit software (Silk Scientific, Inc., Orem, UT). Great care was taken in order to assure correct calibration of the abscissa (time) and ordinate (Absorbance) scales. Finally, the X-Y data files were imported to DADiSP (DSP Development, Cambridge, MA) digital signal processing software.

Calibration Procedure

The Sieglaff-McKelvey rheometer was operated in the constant shear stress mode by adjusting and maintaining constant applied pressure to the load frame [7]. Applied nitrogen pressures of 20, 40, 60, 80 and 100 psi were routinely selected for each lot and class of Automate Red B microcapsule. The calibrating fluid was heated to 80 C, microcapsules were added to approximately the 0.05% (w/w) level and the hot fluid was carefully swirled to disperse the microcapsules. The fluid was poured into the barrel/die assembly and left to cool before engaging the piston to achieve constant loading for each of the applied pressures, noted above. A chart recording of the microphotometer output was obtained along with load and piston velocity. The microphotometer chart recording typically showed small peaks (intact particles) and large peaks (ruptured microcapsules). Peak height analysis, either manually or with DADiSP software enabled calculation of rupture extent (%). The load channel recording allowed calculation of shear stress at the capillary wall. The

velocity signal was not routinely used for calculations or calibration. Ideally, the velocity channel gives shear rate which combines with the load channel (shear stress) information to yield viscosity. Periodically the load and velocity channel signals were combined to verify microcapsule-calibrating fluid mixture viscosity, especially at high shear stress. At each of the shear stress levels, 10 to 20 minutes of extrusion were permitted and the extrudate was collected on a microscope slide. Examination of the extrudate by light microscopy allowed determination of rupture extent by manual counting of ruptured and intact microcapsules.

Results and Discussion

Calibrating Fluid Characterization

MACH I calibrating fluid (part number CF 232) was observed to exhibit dilatant behavior as well as a significant temperature coefficient of viscosity. Dilatancy was confirmed by constant shear stress experiments (at 295 K) between 56 and 361 kPa with the Sieglaff-McKelvey capillary rheometer. No microcapsules were added to the calibrating fluid during this study. The log of shear rate was plotted against log shear stress, revealing a linear relationship ($r = 0.95$) with slope $= 0.72$ and intercept = 1.7 kPa. Thus, the viscosity was calculated to increase from 1.44 kPa·s at 26.6 kPa to 2.4 kPa·s at 165 kPa. The temperature dependence of viscosity was determined with a Brookfield cone and plate viscometer which was fitted with a thermostated sample cup and chiller/circulator. A plot of log shear viscosity (in cP) versus 1/T revealed a linear relationship ($r = 0.991$) with slope = 4505 log(cP)·K and intercept = -10.13 log cP. Thus the activation energy for viscous flow was 16.3 kJ/mol at 298 K, room temperature.

Despite the possibility that these effects might cancel during a calibration experiment, it is doubtful that there is any influence of viscous heating in the capillary rheometer calibration. This conclusion is supported by three facts. First, dilatancy was observed with capillary rheometry. Second, the capillary/die/barrel assembly had a huge heat capacity because these metal pieces are in intimate contact with a large heating mantle. Third, heat dissipation within the capillary is relatively

efficient due to the small lumen diameter (0.65 mm), making localized heating highly unlikely. So, the significant temperature coefficient of viscosity necessitated a constant temperature for maximum calibration reproducibility. Dilatancy of the calibrating fluid contributed to a small bias in the estimation of shear stress at the capillary wall. It is highly likely that there was not a linear stress profile from the capillary center to the wall because viscosity of the fluid at the wall was higher due to shear thickening. Therefore, all shear stress values, as calculated from the load channel response, should be also corrected for shear thickening using the correction factor and equation cited above.

Microphotometer Instrumentation

The microphotometer was evaluated in two respects. Peak-to-peak noise with flowing calibrating fluid was approximately 0.0012 AU and did not change at either lower or higher flow rates. This rather high noise figure was due to capacitive loading from the long cables connecting the photocells with the log ratio amplifier. Detector drift was approximately 0.0003 AU/hr. The response time was not altered by electronic filtering of the amplifier output. We wanted the electronics to accurately follow the optical density within the narrow cone of light passing between the ball lenses. The residence time of a microcapsule in this region varied from several hundred milliseconds to just tens of milliseconds, depending on the flow rate. Peak heights approaching 0.08 AU were recorded for the largest microcapsules and amplitudes of about 0.02 AU were obtained for the smallest microcapsules. LED emission at 555 nm [8] was well matched to the 514 nm absorption maximum of Automate Red B [9]. The optical background absorbance signal from the calibrating fluid was negligible.

Quite a bit of time was spent improving the microphotometer design. A dual channel reflection/transmittance instrument has been constructed. A detailed treatment of the optics and electronics of this instrument are beyond the scope of this presentation. Multifiber bundles were arranged to enable both transmittance and reflection sensing of the capillary contents. Intact

microcapsules that are close to the capillary wall are detected by the reflection sensor while the transmission sensor detects near and far ruptured microcapsules. This should yield a more accurate counting of particles that experience shear stress at the capillary wall. There was not sufficient time to prepare an evaluation of this new instrumentation. Look for this in a future publication.

Automated Peak Height Analysis

The basic premise to microcapsule counting and rupture event discrimination by peak height analysis is consistent with photon counting [10]. Intact microcapsules, irrespective of size, should yield small peaks because the dye minimally interacts with the light beam while it is contained in the core. Upon rupture, the core liquid will experience significant shear and velocity gradients which will transport the dye away from the microcapsule, resulting in much larger absorption peaks. Randomized radial positioning of the microcapsules in the observation region was not taken into account.

A complete calibration sequence was used for the peak height analysis, i.e. recordings at 20, 40, 60, 80 and 100 psi. Each of the microphotometer traces was imported into DADiSP and the baselines were normalized to zero absorbance. Next, peaks were located using the GETPEAK function. Three parameters must be specified to enable this function: the minimum amplitude of a peak, the minimum number of points in a peak and the minimum valley to peak distance. Figure 2 shows the located peaks from a typical recording. The GETPEAK parameters were optimized for individual recordings to ensure accurate registration of peaks. Then, the peak amplitudes were sorted and ordered, in decreasing amplitude, using the SORT command as shown in Figure 3. The abscissa axis is arbitrary, here. The peak height distribution shows three plateaus. The first plateau extends from 0 to about 4.4, the second plateau goes from 4.4 to about 9.6 and the last plateau extends beyond 9.4. Use of the ZOOM and CURSOR commands reveals that ordinate values of zero begin at 9.7, or peak number 79. Therefore, 79 "true" peaks were located in the

signal. The GETPEAK function effectively eliminates detector electronic noise, provided the execution parameters are properly chosen. Three types of peaks are possible: peaks from unruptured microcapsules, from ruptured microcapsules and from various combinations (broken and intact) of multiple microcapsules. The feature at 4.4 (peak # 36) represents a relatively significant increase in peak amplitude which we have assigned to the transition between broken and intact microcapsules. There is roughly a three-fold increase in peak amplitude to the left of peak # 36. Following the amplitude distribution to the left in Figure 3, there is a fairly smooth increase in peak amplitude until 0.4 . The very large peaks, approaching 0.07 AU, probably indicate multiple peaks of some type. Due to an inability to confine microcapsules infinitesimally close to the capillary wall, we can only designate these as single rupture events. The transition from ruptured to intact microcapsules was carefully evaluated for each of the five recordings in a complete calibration run. The length of the plateau representing intact microcapsules increased with decreasing shear stress. The signal level of the largest amplitude peak in this segment was compared for each of the five recordings. At the lowest shear stress the fewest number of microcapsules ruptured, so it was often difficult to clearly identify this transition. In this situation, the largest amplitude intact peak values were pooled and an average value was used to locate the transition region with more confidence. After identifying the number of peaks in each of the segments, the rupture % was directly calculated, as in Figure 3, 36 rupture events divided by 79 non rupture events is equivalent to 45.6 % rupture. Identical calculations were performed for each of the applied pressure levels.

Optomechanical Response Characteristics

Plots of % rupture versus corrected shear stress indicate the optomechanical response characteristics for a given CAMES™ sample. In the past, both optical microscopy and a manual version of peak height analysis were performed for rupture response calibration. Figure 4 shows data for the two calibration techniques for the 63-74 μm fraction of production lot 19-67A. Figure 5 shows a rupture response plot for a similar CAMES™ sample (production lot 19-67A, 74-90

μm) using the automated peak height analysis procedure, described above. There are distinct differences. The calibration results from Figures 4 and 5 can be quantitatively compared using linear regression results. Optical microscopy and manual peak height analysis yield a regression slope of 0.80 %/kPa, as shown in Figure 4. The regression slope for the calibration results in Figure 5 is 0.14 %/kPa. This is inconsistent with theory since a larger particle should be more susceptible to rupture, hence, will have a larger slope in such a plot. It is quite likely that error were introduced when the stripchart recording was converted to a digital data set. The automated peak height analysis is a viable approach but needs to be optimized and validated before the results are accepted for calibration purposes. Manual counting of peaks from the stripchart microphotometer recording and of particles in the rheometer extrudate is routinely used to generate % rupture data.

A closer examination of Figure 4 reveals details of microcapsule rupture that can be used to specify the microsensors. Since the plots are linear, the slope is an indication of rupture sensitivity, i.e. the change in % rupture with incremental change in shear stress. The greater the slope the greater the tendency for rupture, implying that small differences in shear stress can be more easily seen with microcapsules that display high rupture sensitivity, compared to lower rupture sensitivity. If the lower limit for optical detection can be somewhat arbitrarily assigned to the 10 % rupture level, this represents the rupture threshold (in shear stress) for a particular microcapsule. Conversely, the upper limit for detection would correspond to nearly complete rupture of the microcapsule ensemble at, say, 90 % rupture. This represents the shear strength of the microsensors. These three parameters, rupture threshold, rupture sensitivity and shear strength can be used to specify the calibrated microcapsules or CAMES™. Both the shear stress range and sensitivity are specified by these three parameters. Note the calibration data of Figures 6 and 7. Figure 6 represents a relatively low rupture sensitivity (0.17 %/kPa) microcapsule (< 44 μm) and Figure 7 shows even less rupture sensitivity (0.08 %/kPa) for this microcapsule (44-53 μm). Lot 9-13-561 was determined to have a 0.4 μm wall thickness and lot 9-13-512 had a 0.87 μm wall. Therefore,

smaller diameter particles and thicker walls result in less rupture sensitivity. These results are consistent with theory.

Conclusions

Improved sensor calibration methods have been developed which have enabled a better understanding of microcapsule response to shear stress during calibration by capillary rheometry. Original observations of dilatancy of the calibrating fluid will require corrections in the computation of true wall shear stress. Advances have been made in the calibration instrumentation and the particle counting procedures. Less than satisfactory improvements have resulted, but work is continuing and we are confident that the final outcome will be positive. Three parameters have been selected for specifying microcapsule calibration, rupture sensitivity, shear threshold and shear strength. The practical significance of these parameters is now much clearer than in the past.

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Figure 1. Microphotometer Flow Cell Assembly

LEGEND

A: SMK die
B: capillary
C: cell body
D: green LED
E: ball lens
F: reference photodiode
G: sample photodiode

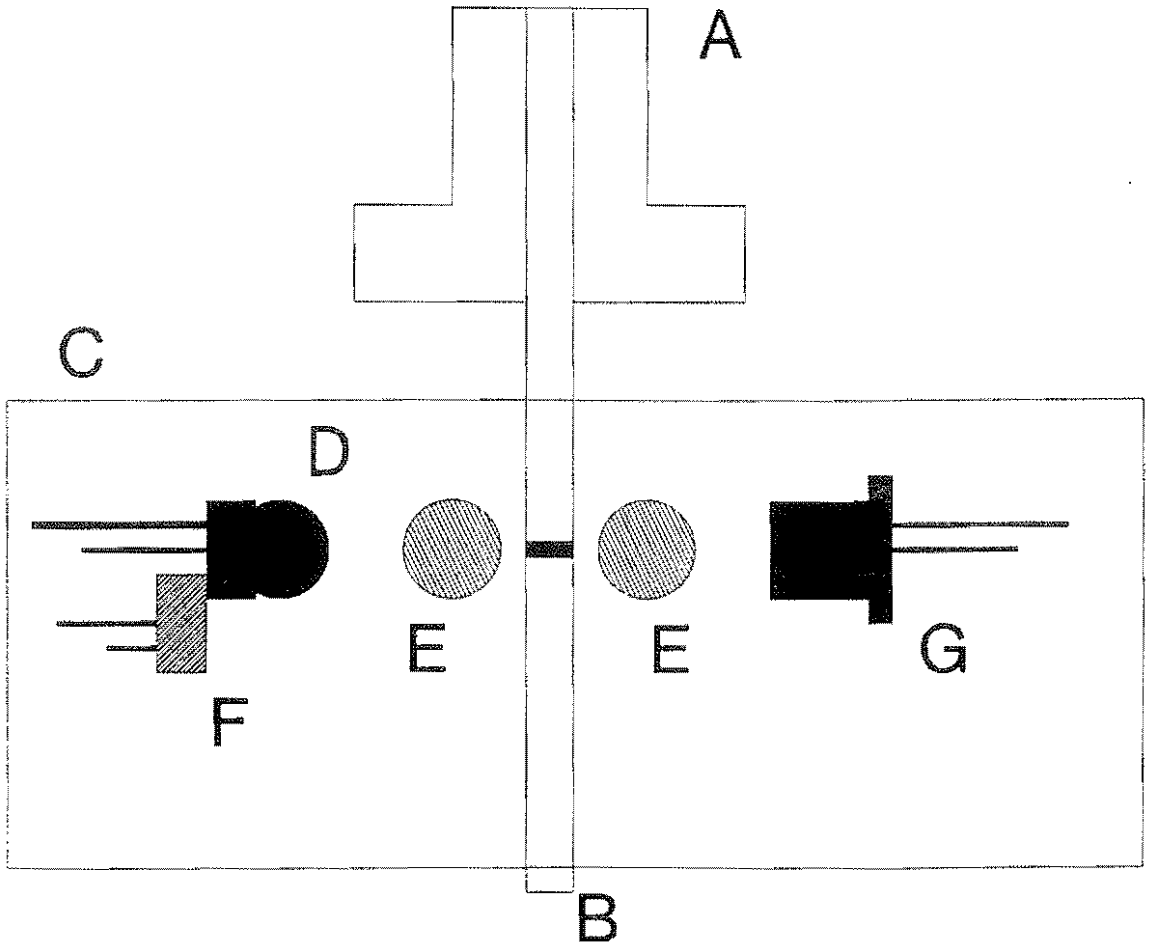


Figure 2. Digitized Microphotometer Recording Showing Located Peaks

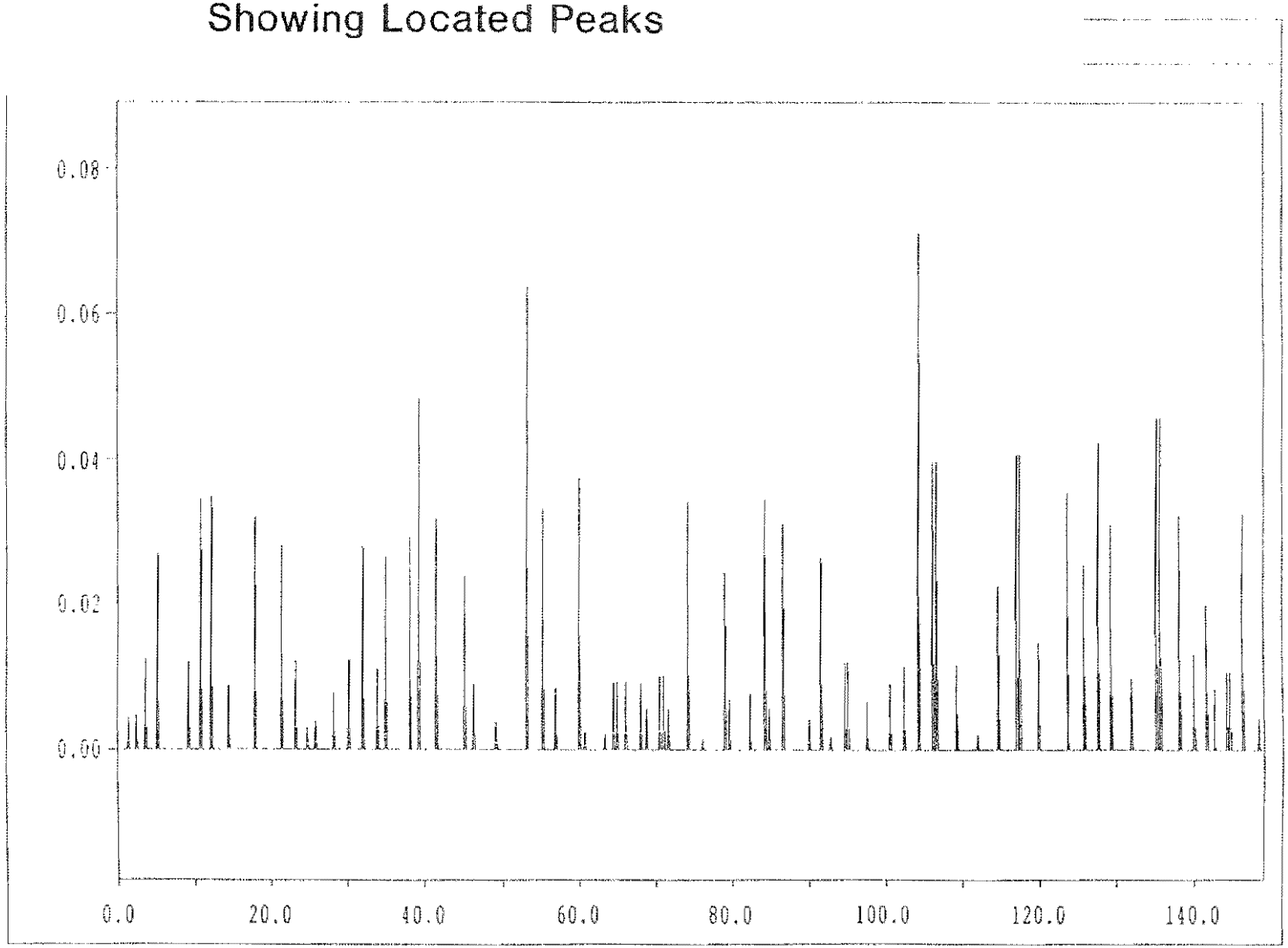


Figure 3. Peak Height Distribution of Fig. 2 Data

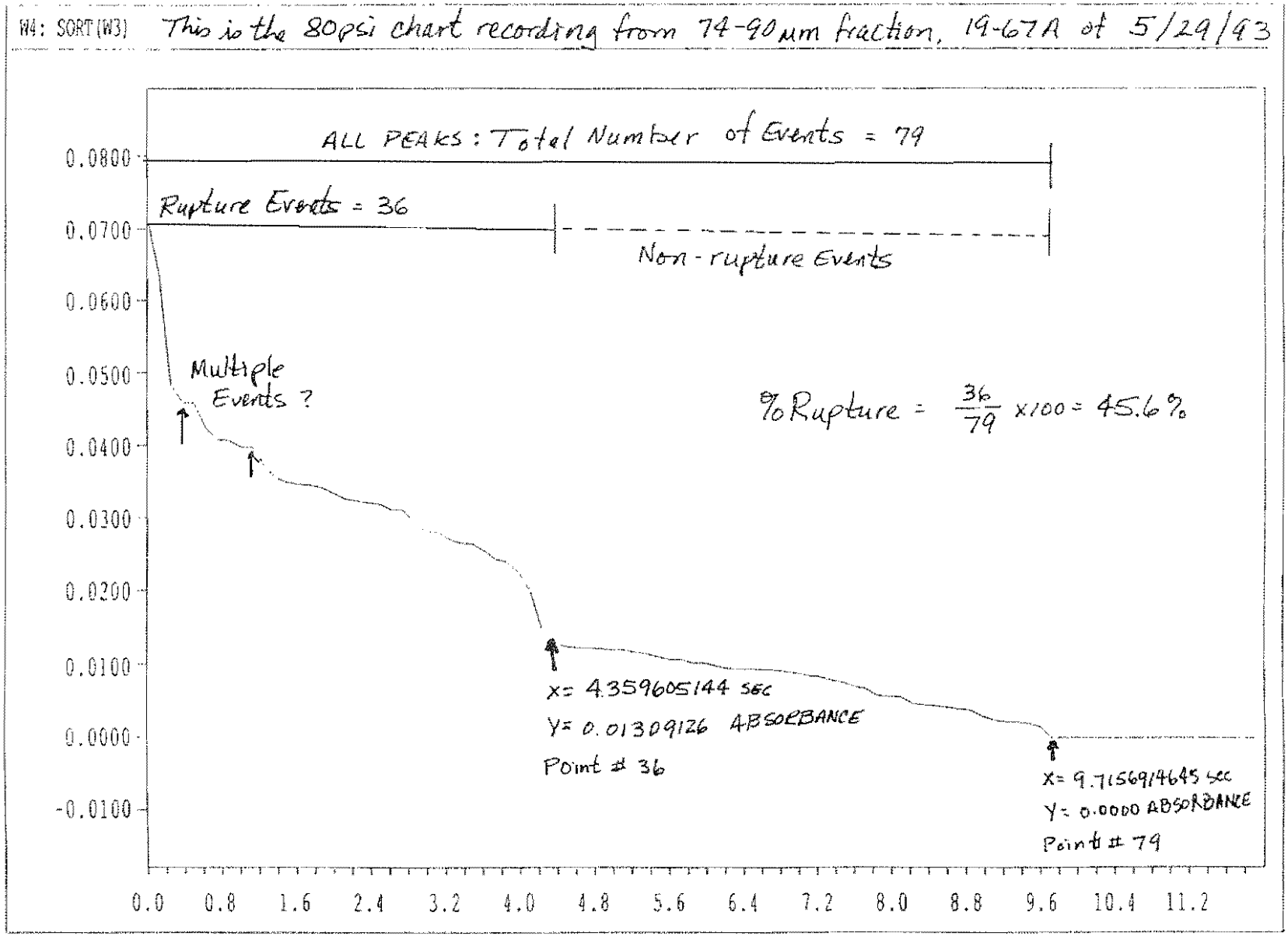
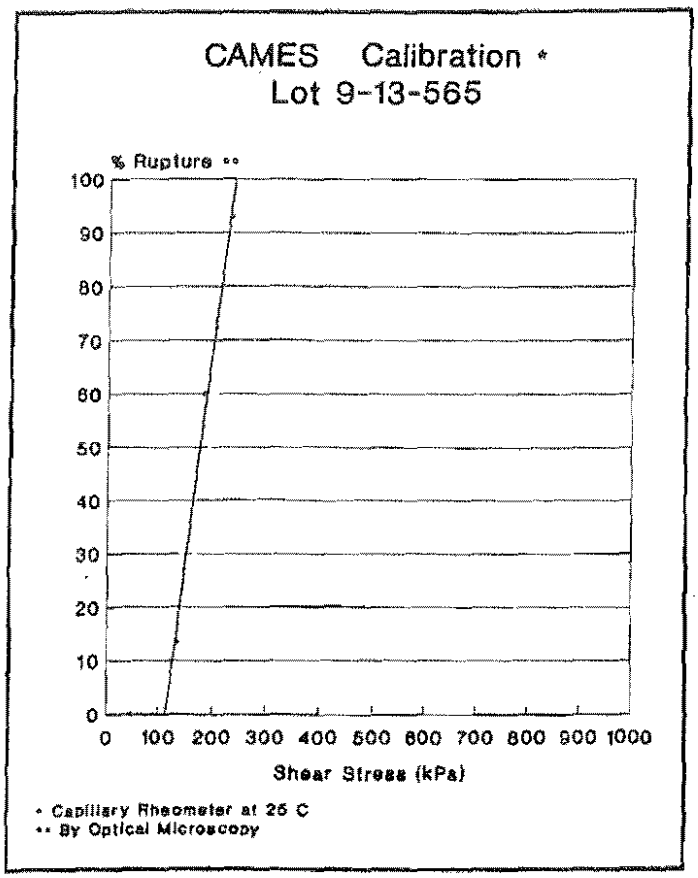


Figure 4. Rupture Response Calibration Using Manual Peak Height Analysis and Optical Microscopy, Lot 9-13-565

Sensor Material	Red Dye in Xylene
Absorbance Maxima, nm	530
Shear Threshold (10% Rupture), kPa	125
Rupture Sensitivity, Slope by Regression	0.80
Shear Strength (90% Rupture), kPa	225



8/31/95

MACH I Inc., 340 East Church Road, King of Prussia, PA 19406 (610) 279-2340 FAX: (610) 279-6605

Figure 5. Rupture Response Calibration Using Automated Peak Height Analysis, Lot 9-13-566

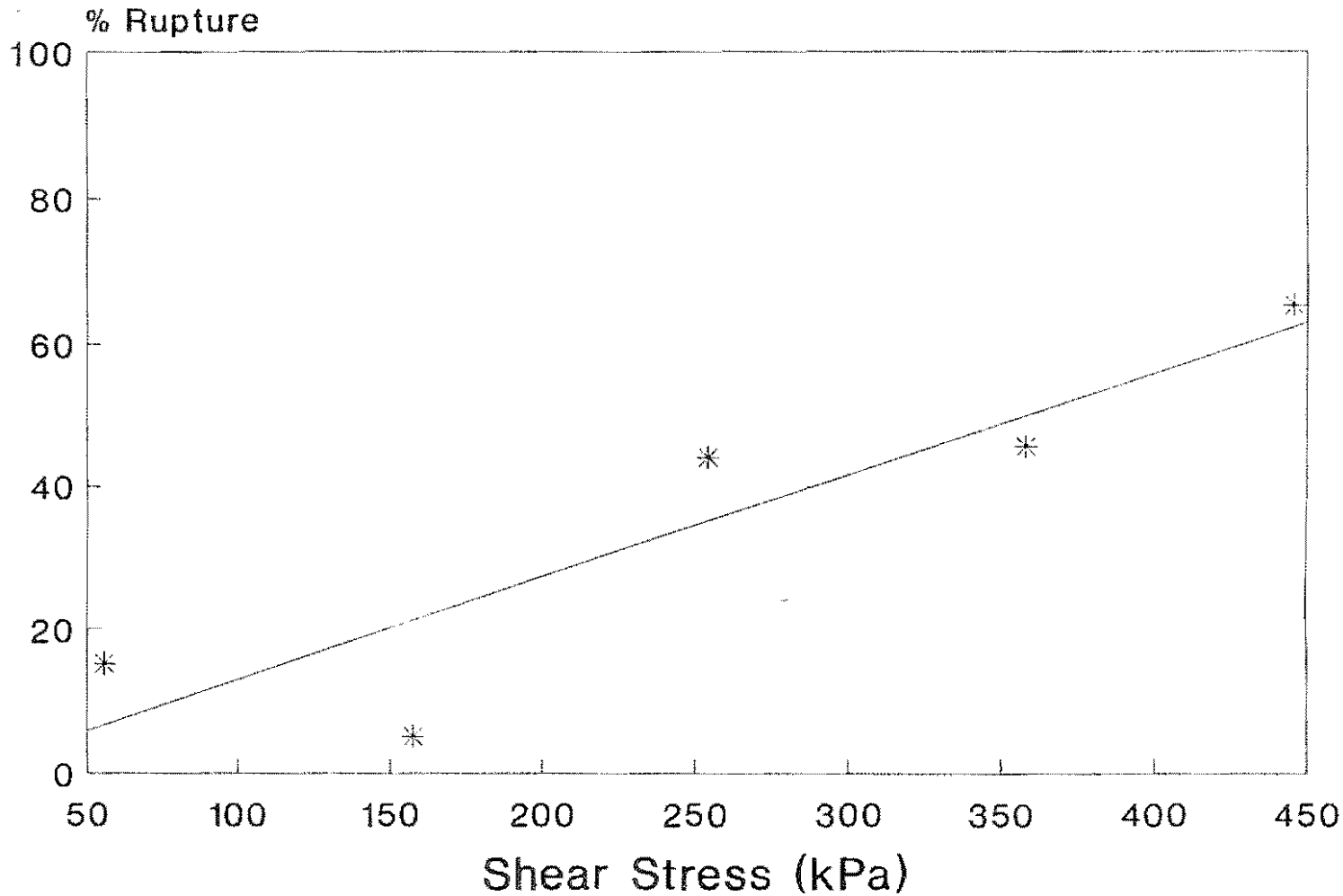
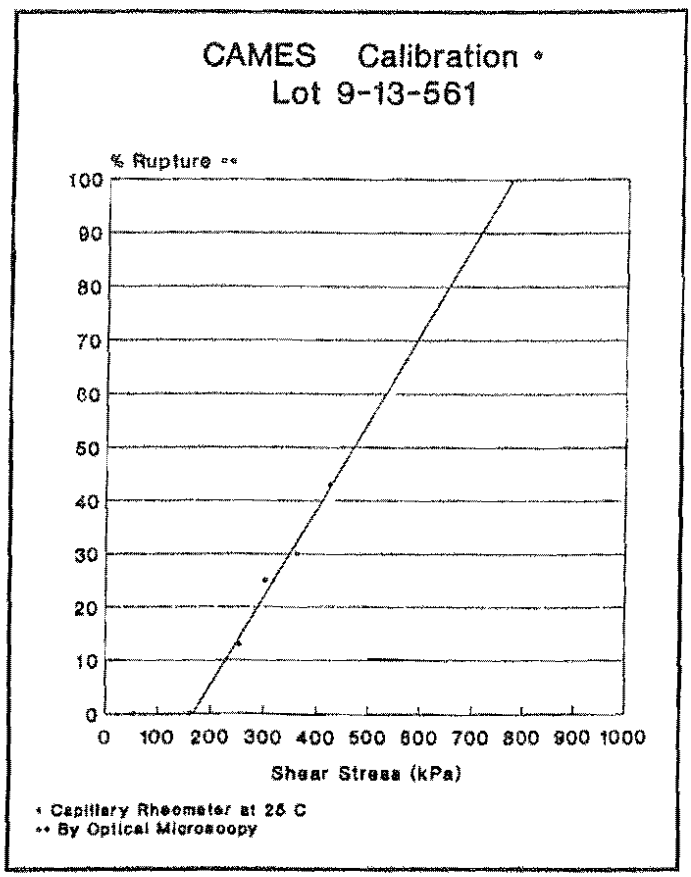


Figure 6. Rupture Response Calibration Using Manual Peak Height Analysis and Optical Microscopy, Lot 9-13-561

Sensor Material	Red Dye in Xylene
Absorbance Maxima, nm	530
Shear Threshold (10% Rupture), kPa	225
Rupture Sensitivity, Slope by Regression	0.17
Shear Strength (90% Rupture), kPa	700



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CONCLUSION

Evaluation on the factors which may effect mixing length

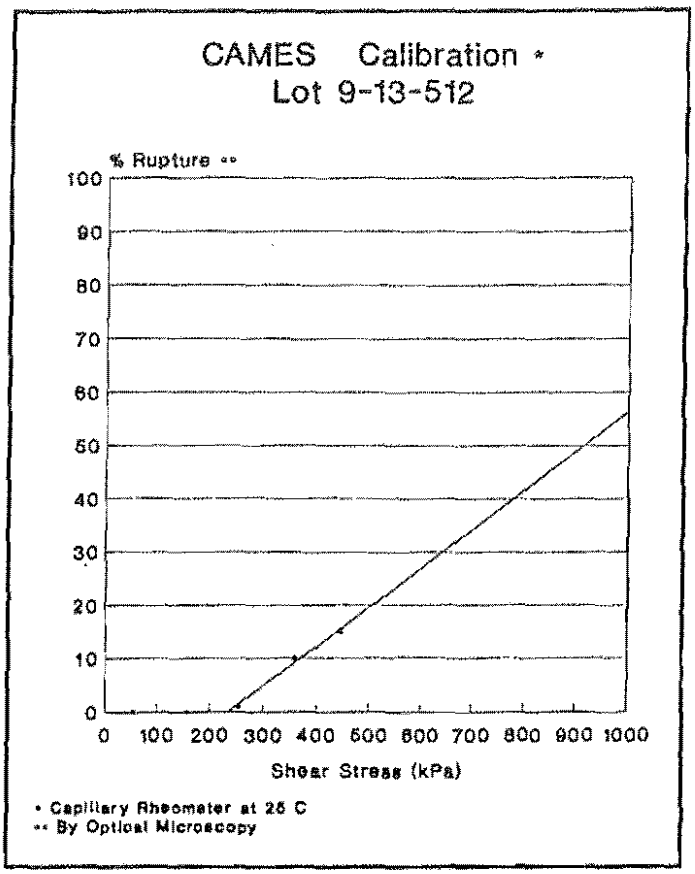
* Screw angular velocity-rpm
* Percentage of channel filled
* Screw stagger

After evaluating these factors, we can tell that the distributive mixing is independent of screw velocity which violates the standard scale-up rules

EXTRUSION DIVISION

Figure 7. Rupture Response Calibration Using Manual Peak Height Analysis and Optical Microscopy, Lot 9-13-512

Sensor Material	Red Dye in Xylene
Absorbance Maxima, nm	530
Shear Threshold (10% Rupture), kPa	375
Rupture Sensitivity, Slope by Regression	0.08
Shear Strength (90% Rupture), kPa	1450



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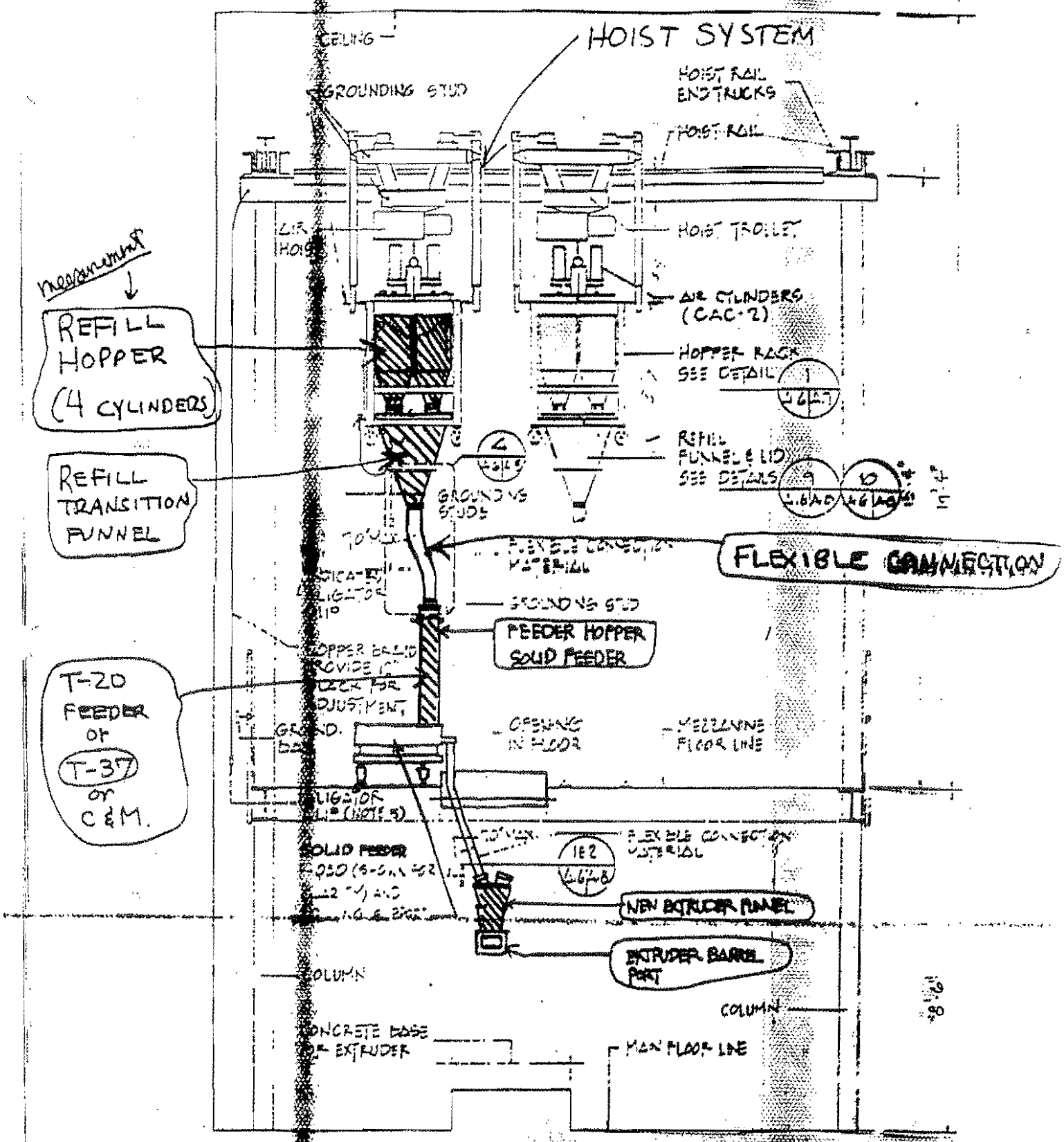
NON-INVASIVE MONITORING OF SEGREGATION PROCESSES

MASAMI NAKAGAWA*
XIAOSHAN LIN**
GRAHAM G.W. MUSTOE**

*Sandia National Laboratories
**Colorado School of Mines

OVERVIEW OF REFILL/FEEDER SYSTEM



SECTION OVERVIEW

NOT TO SCALE: 1/2" = 1'-0"

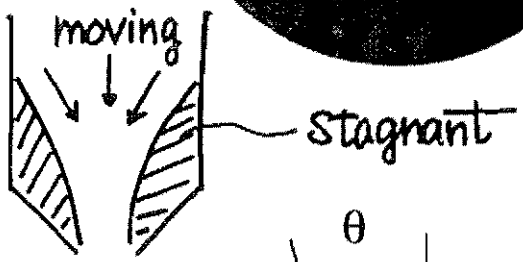
CPOCP

FOR OFFICIAL USE ONLY

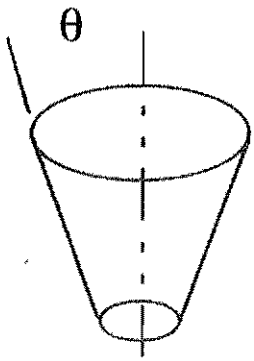
Are particles:
1.coarse
2.free flowing
3.nondegrading
4.nonsegregating

Yes

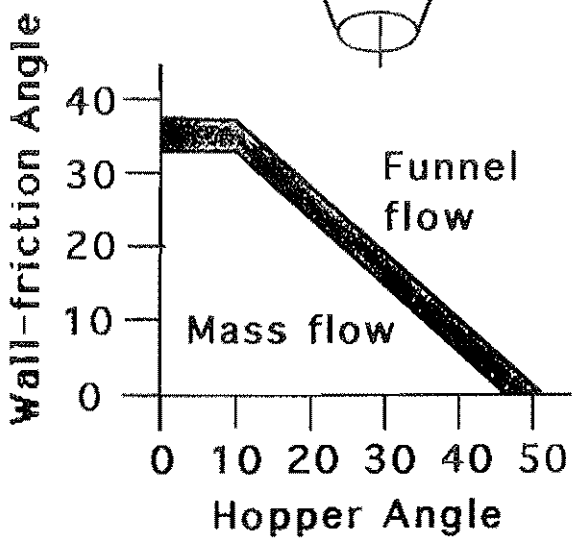
No

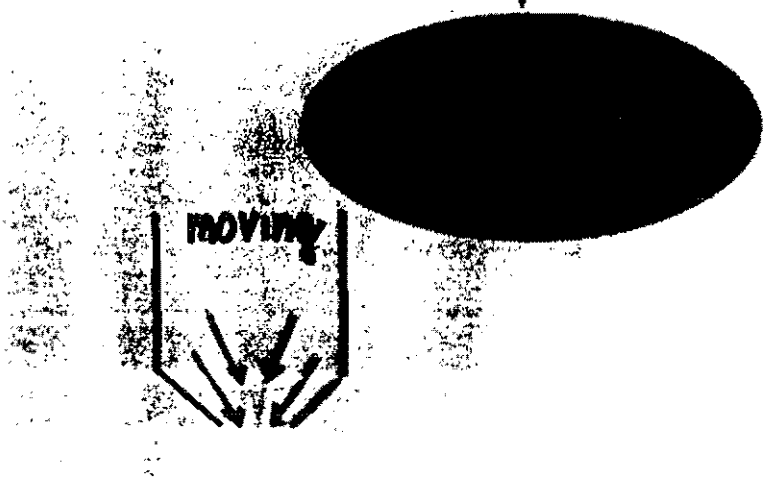


- Measure wall-friction angle φ
- Measure Hopper angle, θ

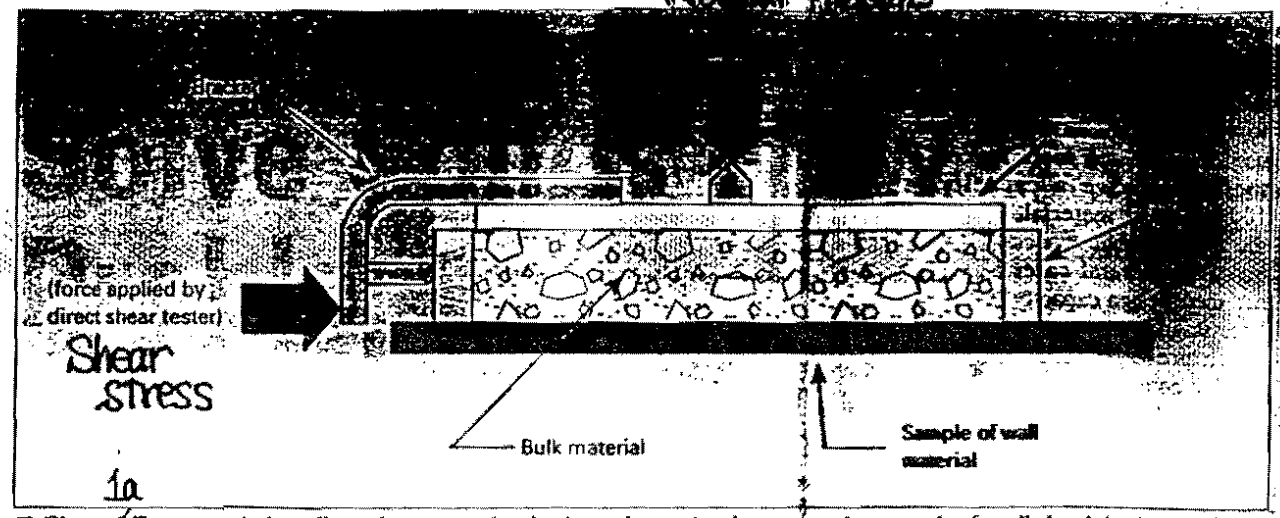


Design chart



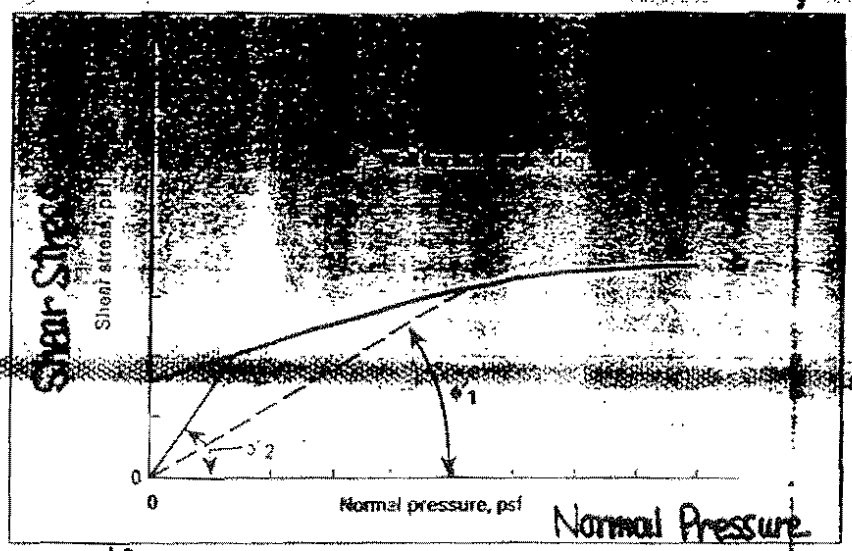


Normal Pressure



1a

■ *Figure 3. Test setup design allows shear stress (see horizontal arrow) to be measured as a result of applied weights (see vertical downward arrow).*



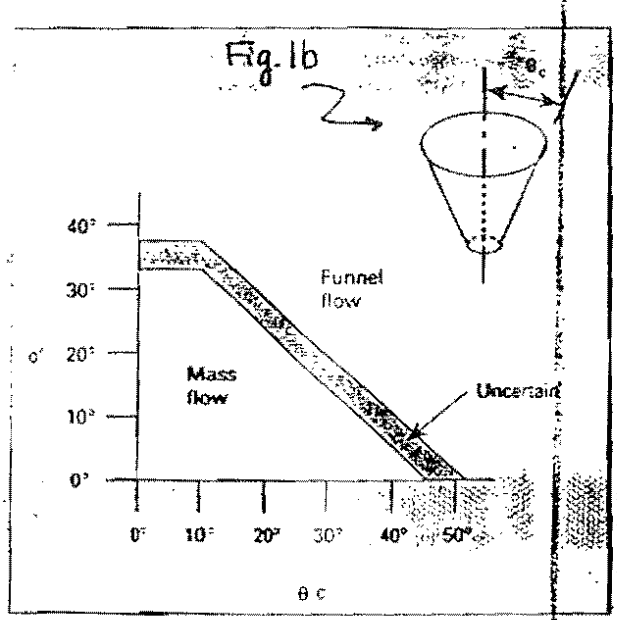
1a

■ *Figure 4. (top) Typical results of the test setup shown in Figure 3 to help engineers determine wall friction angle.*

Factors that influence wall friction

- Wall Material
- Temperature ←
- Moisture ←
- ~~Corrosion~~
- Abrasion Wear
-

Fig. 1b



1c.

■ *Figure 5. Design chart for a conical hopper allows the designer to know whether mass-flow or funnel-flow will take place. It has a built-in margin of safety.*

May 1992
Chemical Engineering Progress
J. Marinelli, C.W. Carson
Jenike & Johanson, Inc.

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

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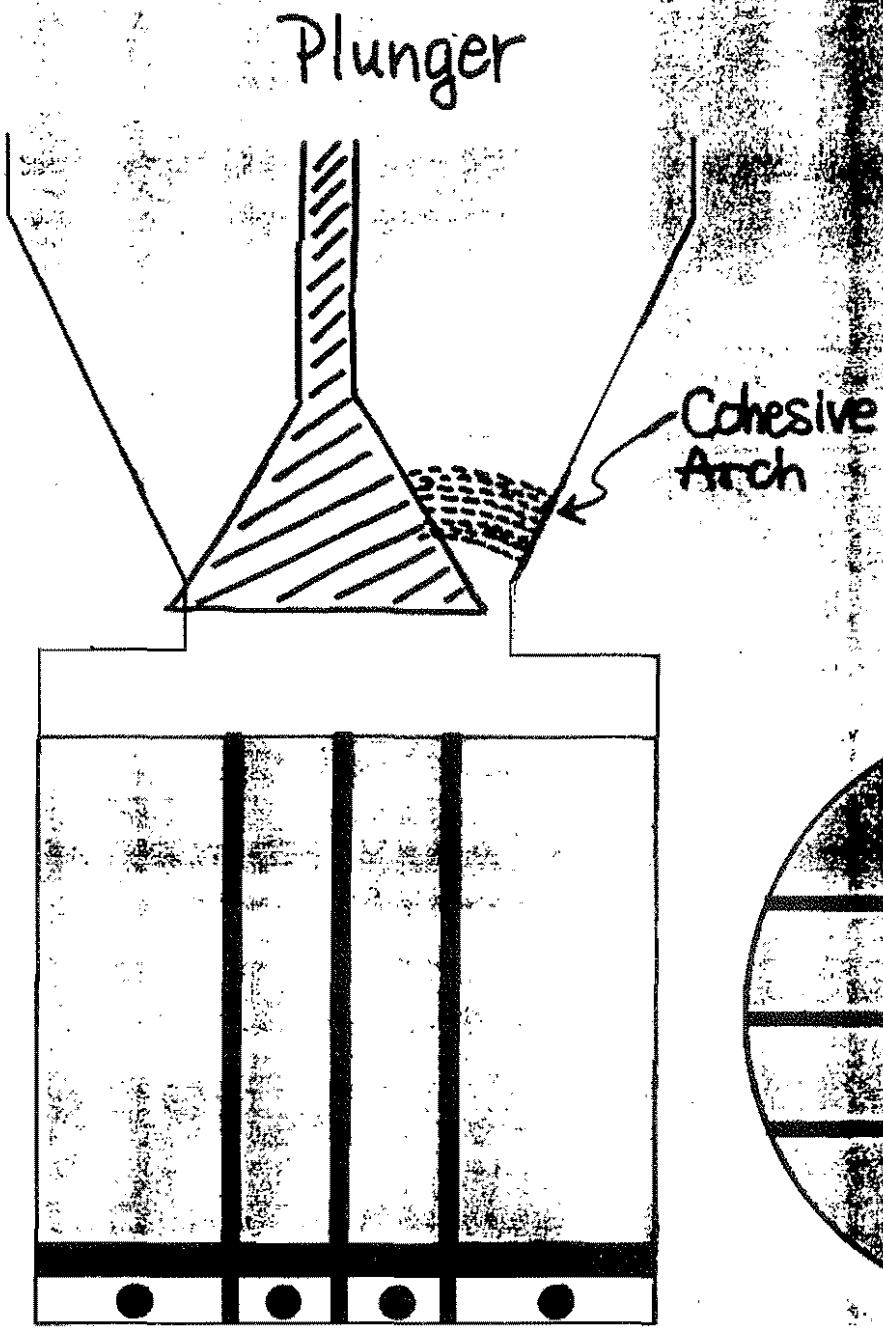
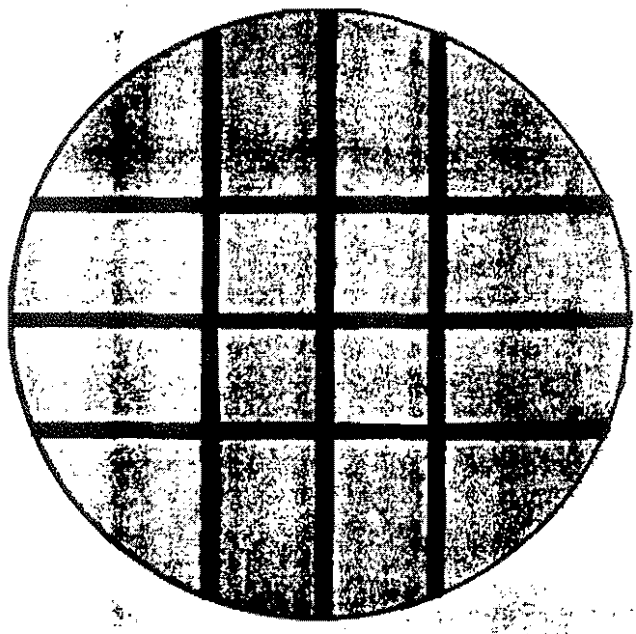


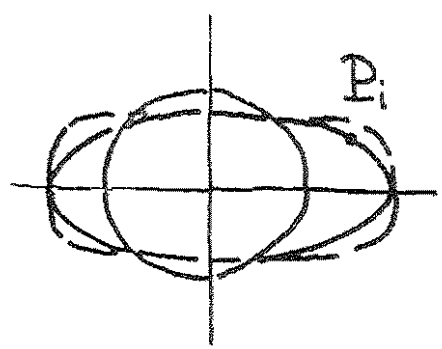


MATERIAL SAMPLING

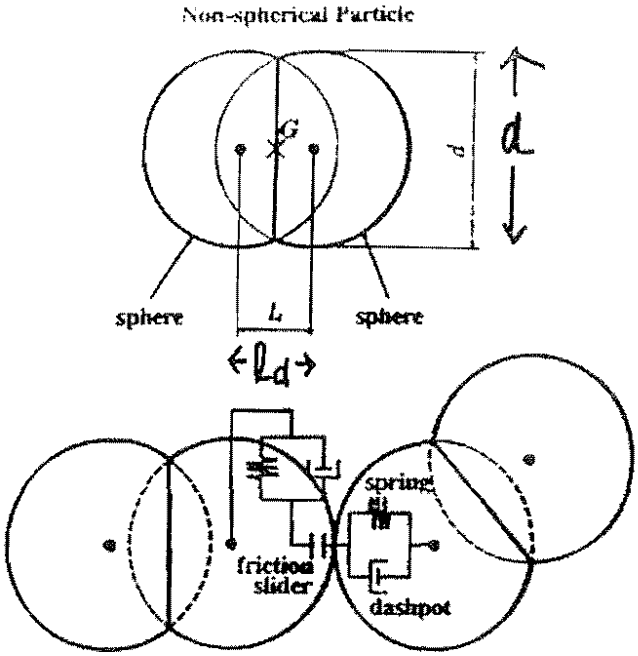
DEM (Discrete Element Method) Simulation

	ADVANTAGES	DISADVANTAGES
CIRCULR PARTICLES	•COMPUTAIONAL SIMPLICITY	•Inherent tendency to roll •Normal force never contribute to moment
POLYGONAL PARTICLES		•Vertices: edge-edge, edge-corner corner-corner •Require a large number of sides to approximate rouded/subangular particles
ELLIPSOIDAL PARTICLES	•Unique outward normal (no singularities on surface) •Easy extension to 3D	

Superquadric



$$f(x_i, y_i) = \left(\frac{|x_i|}{a_i}\right)^{n_i} + \left(\frac{|y_i|}{b}\right)^{n_i} - 1 = 0$$



$$A_s = \frac{d}{d+\ell_d}$$

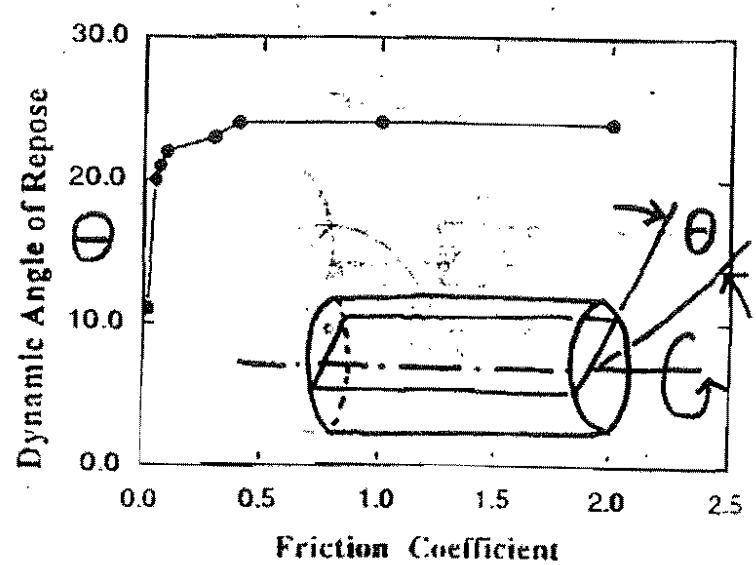
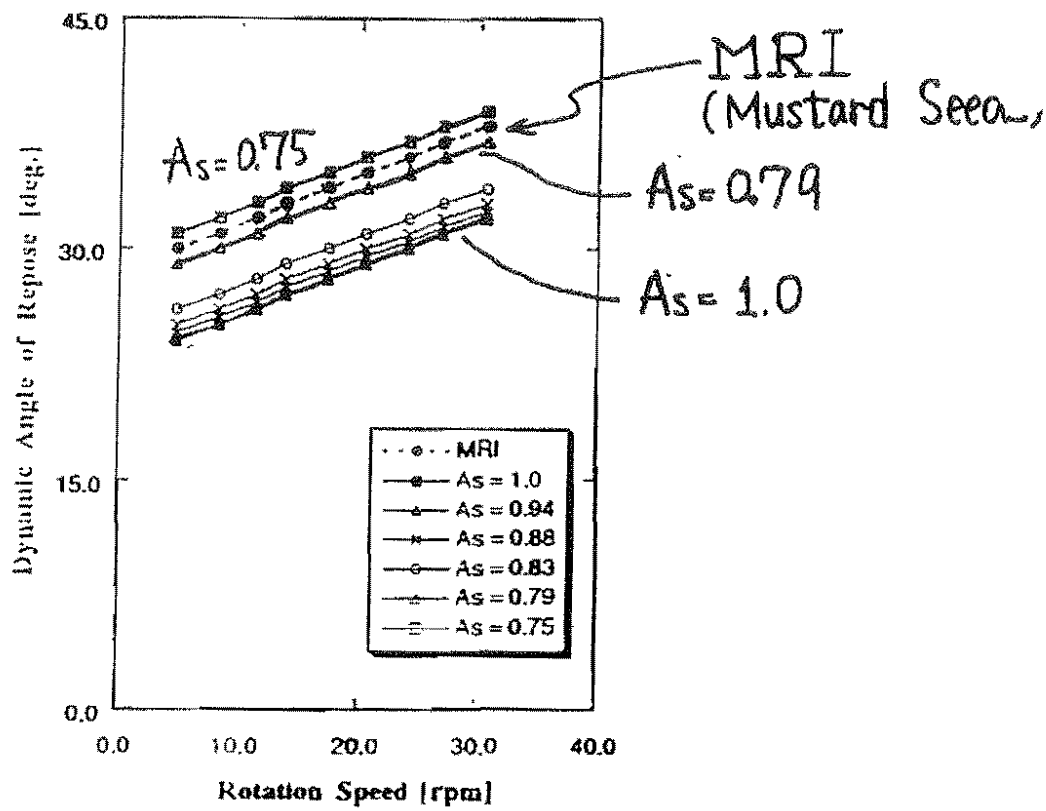
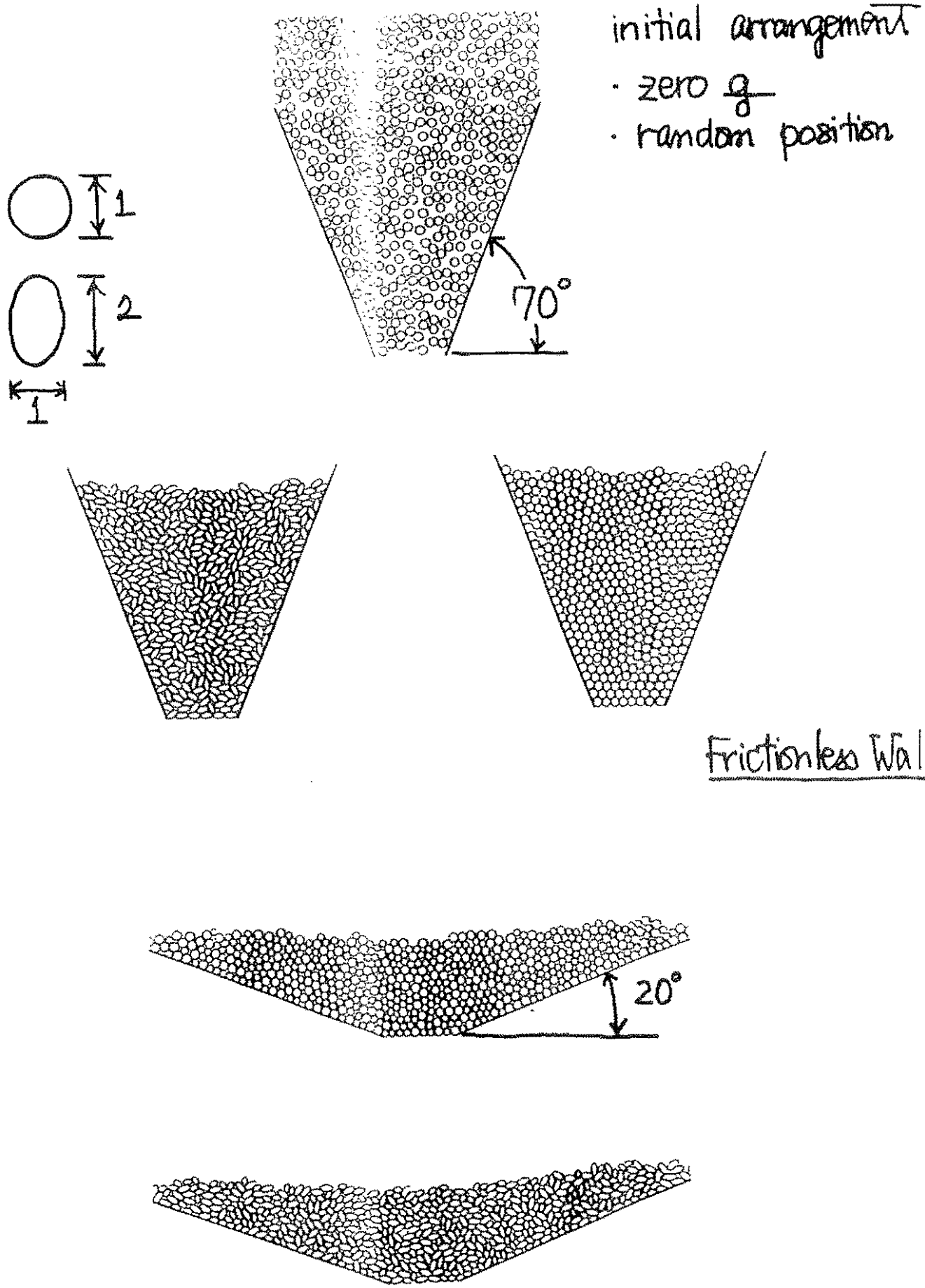


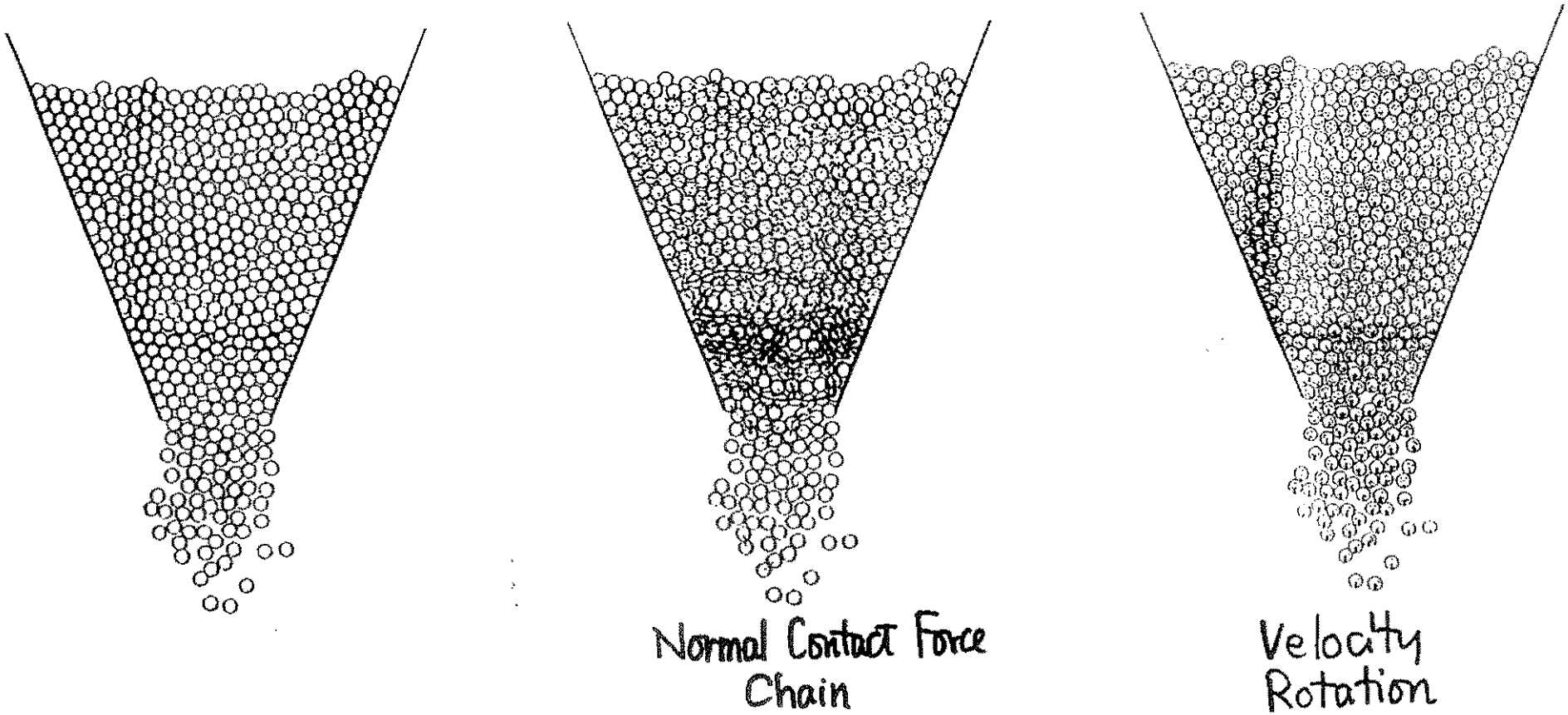
FIGURE 1. MODEL OF CONTACT FORCES

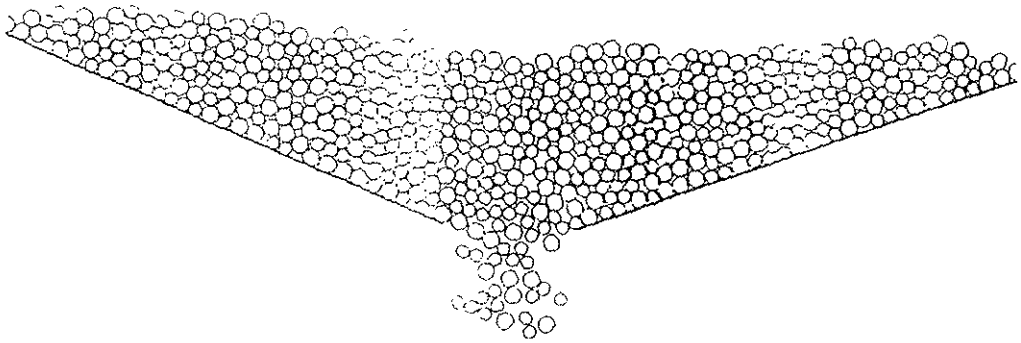


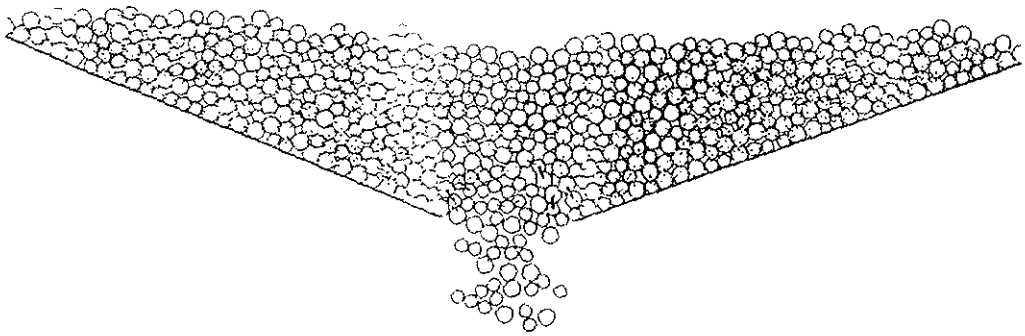
Yamane, Tanaka, Tsuji
(Osaka Univ.)
Nakagawa, Altobelli
(Lovelace Inst.)

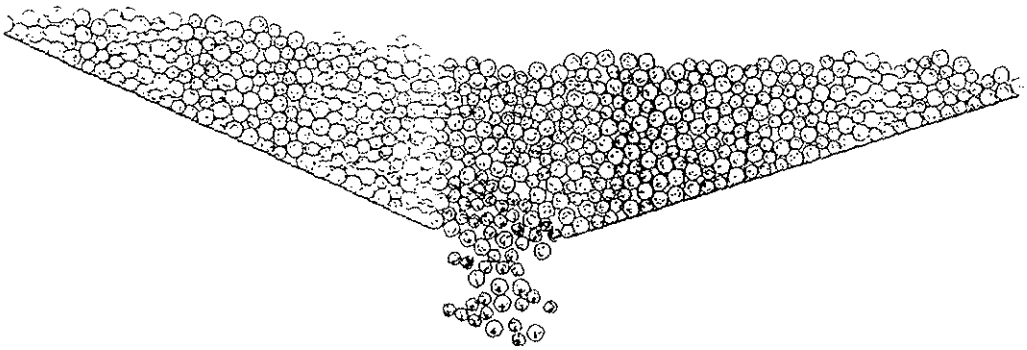
FIGURE 3. EFFECTS OF NON-SPHERICITY ON DYNAMIC ANGLE OF REPOSE

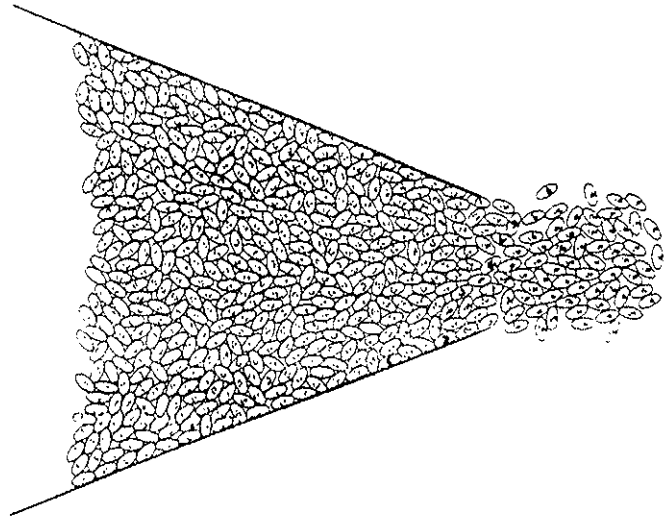

initial arrangement
· zero g
· random position
1
2
1
70°
Frictionless Wall
20°

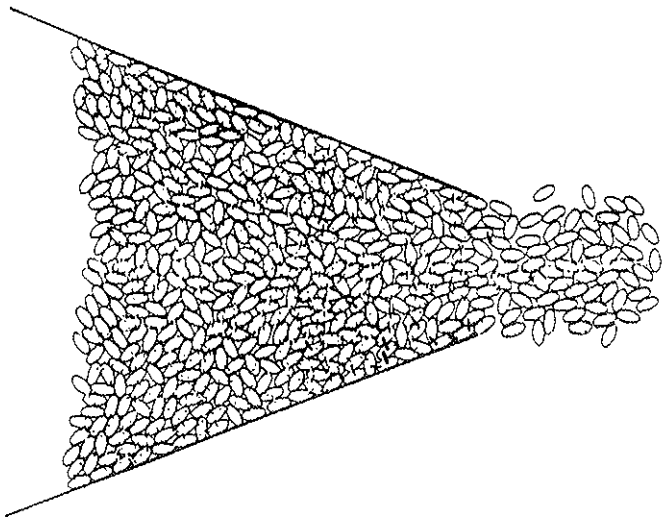

Normal Contact Force
Chain
Velocity
Rotation

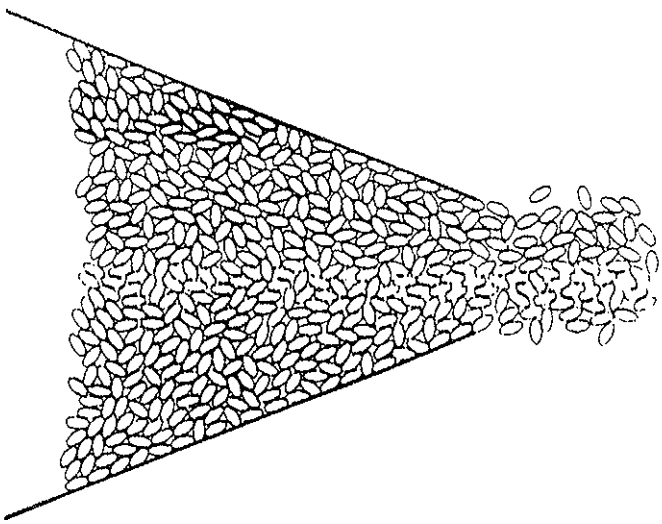


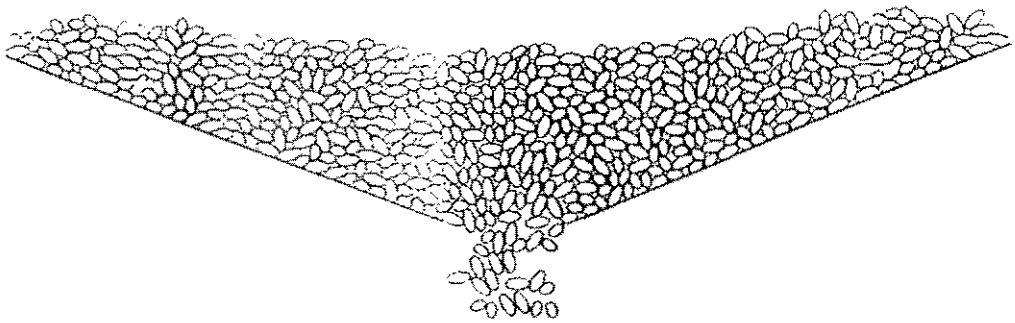


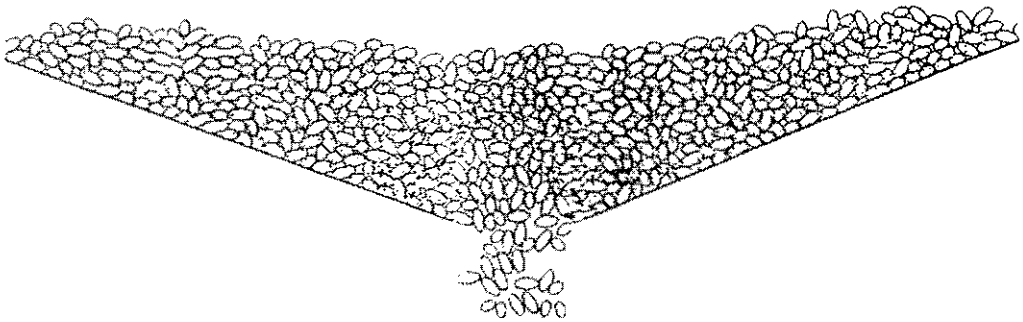


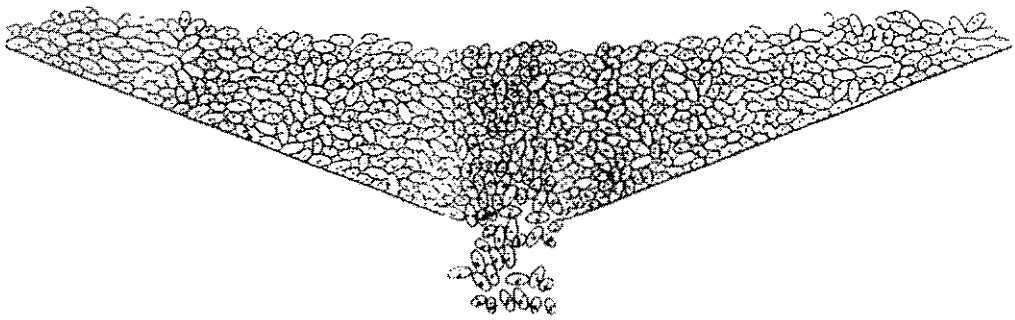


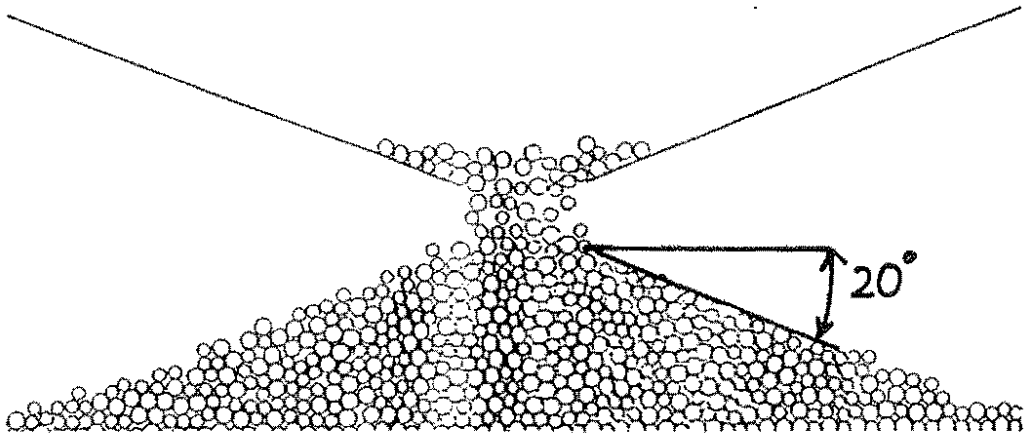


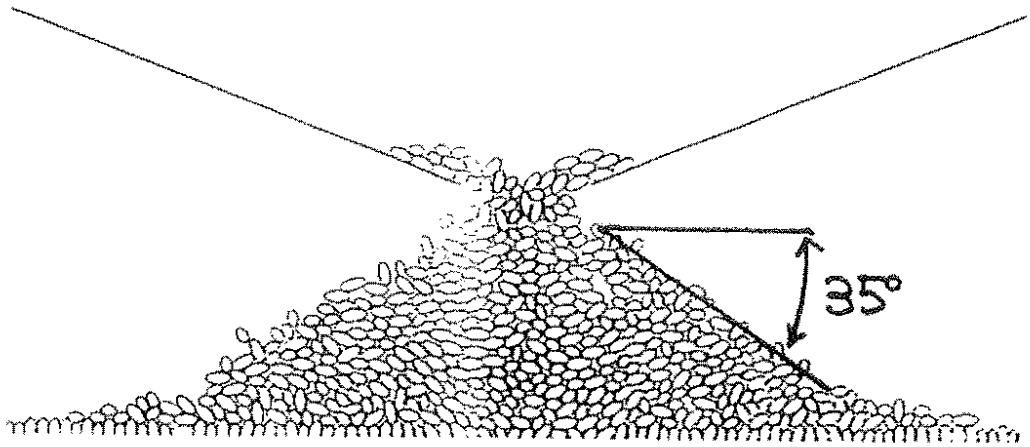






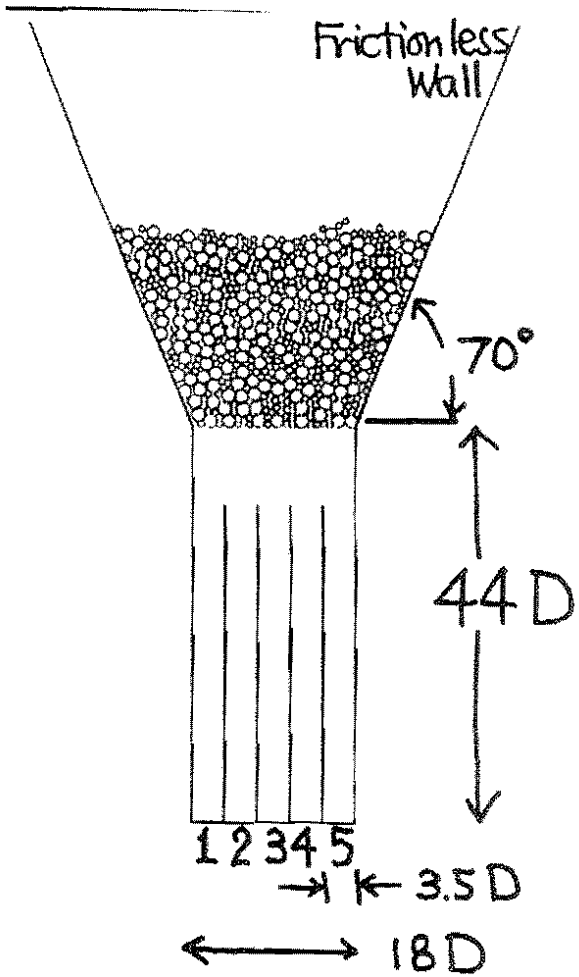


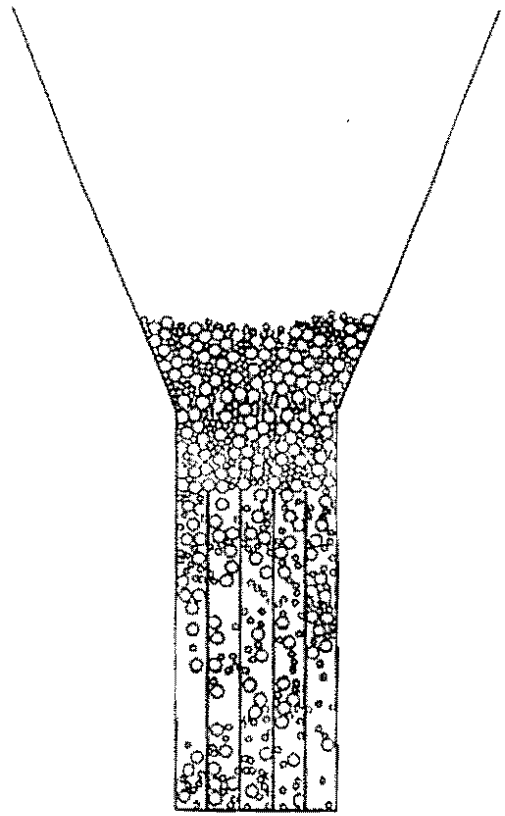

20°

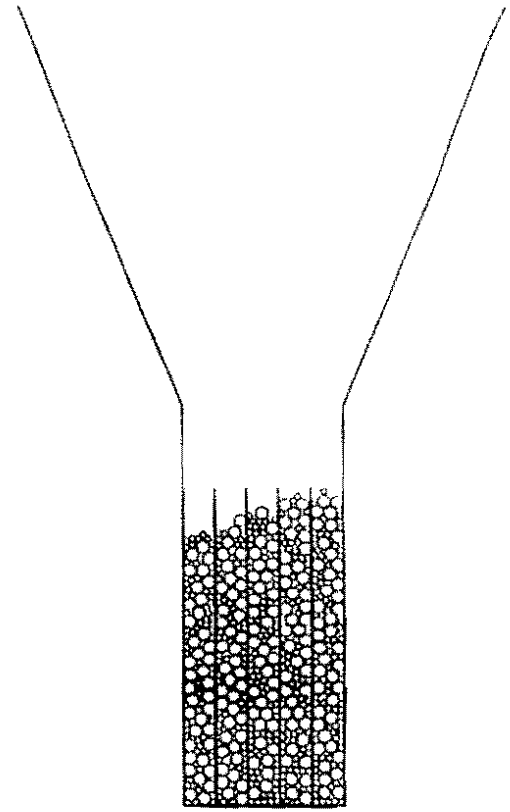

35°

# of small particles

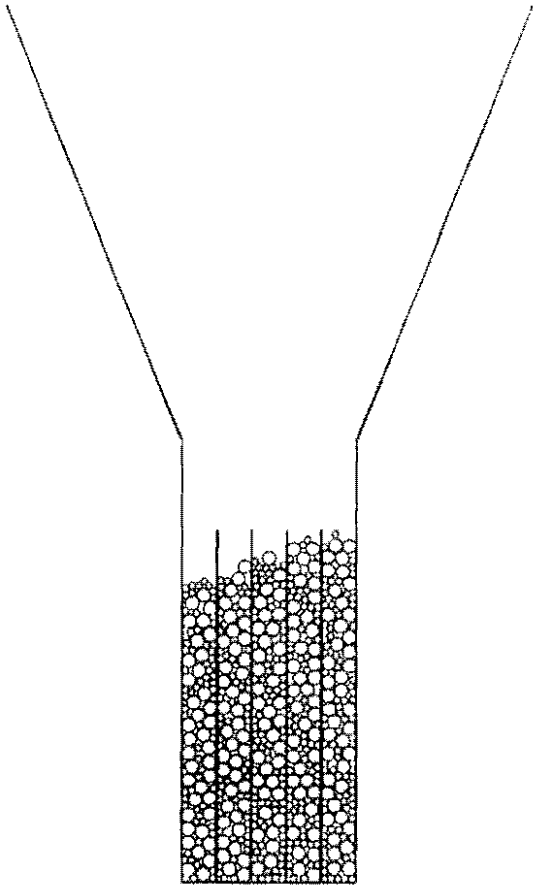
# of Large particles = 200

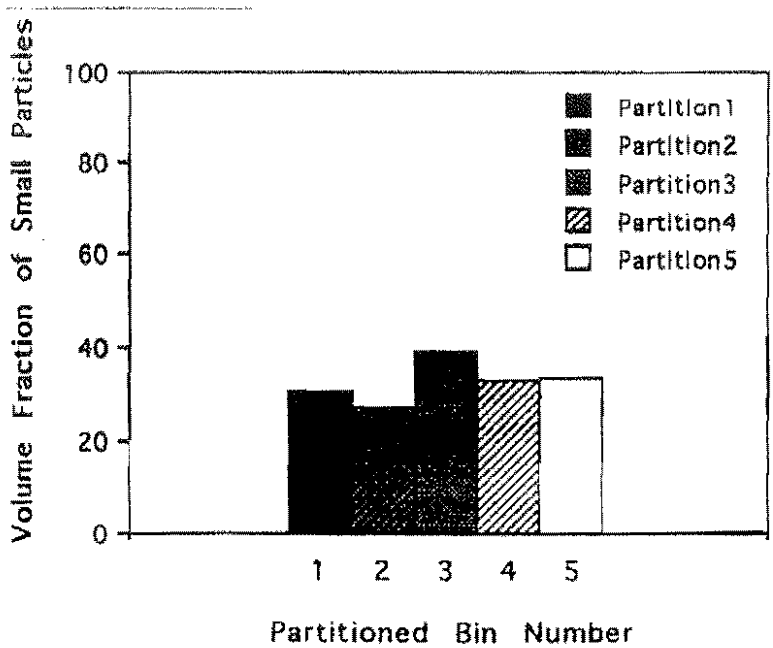






$$\frac{\text{Small}}{\text{Large}} = \frac{\frac{1}{2}D}{D} = \frac{1}{2}$$




Volume Fraction of Small Particles
100
80
60
40
20
0
Partition1
Partition2
Partition3
Partition4
Partition5
1
2
3
4
5
Partitioned Bin Number

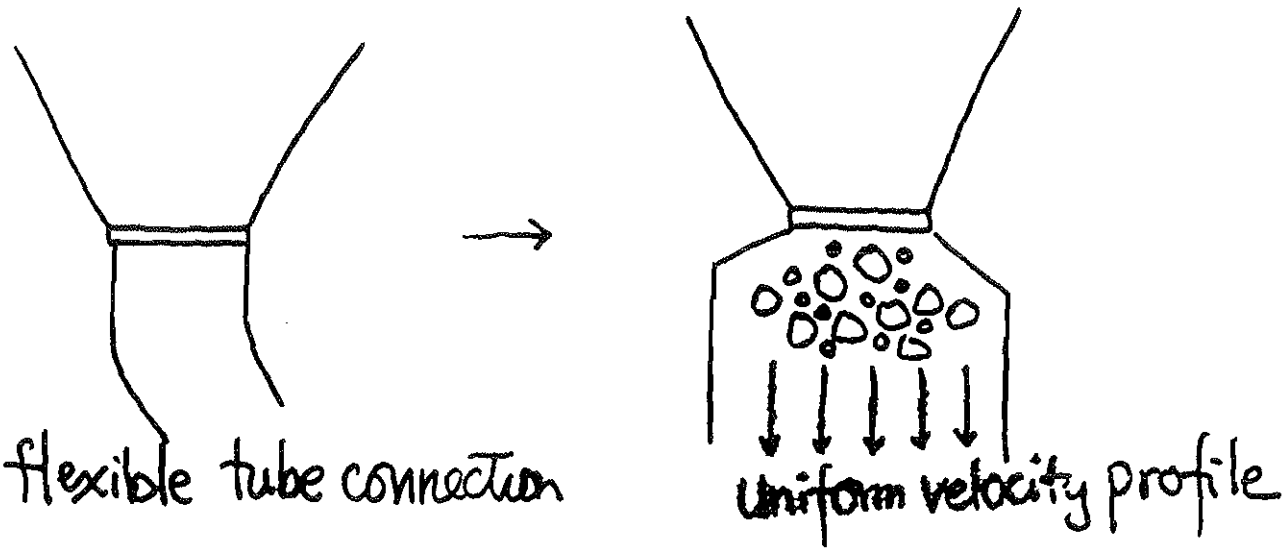
Improvements

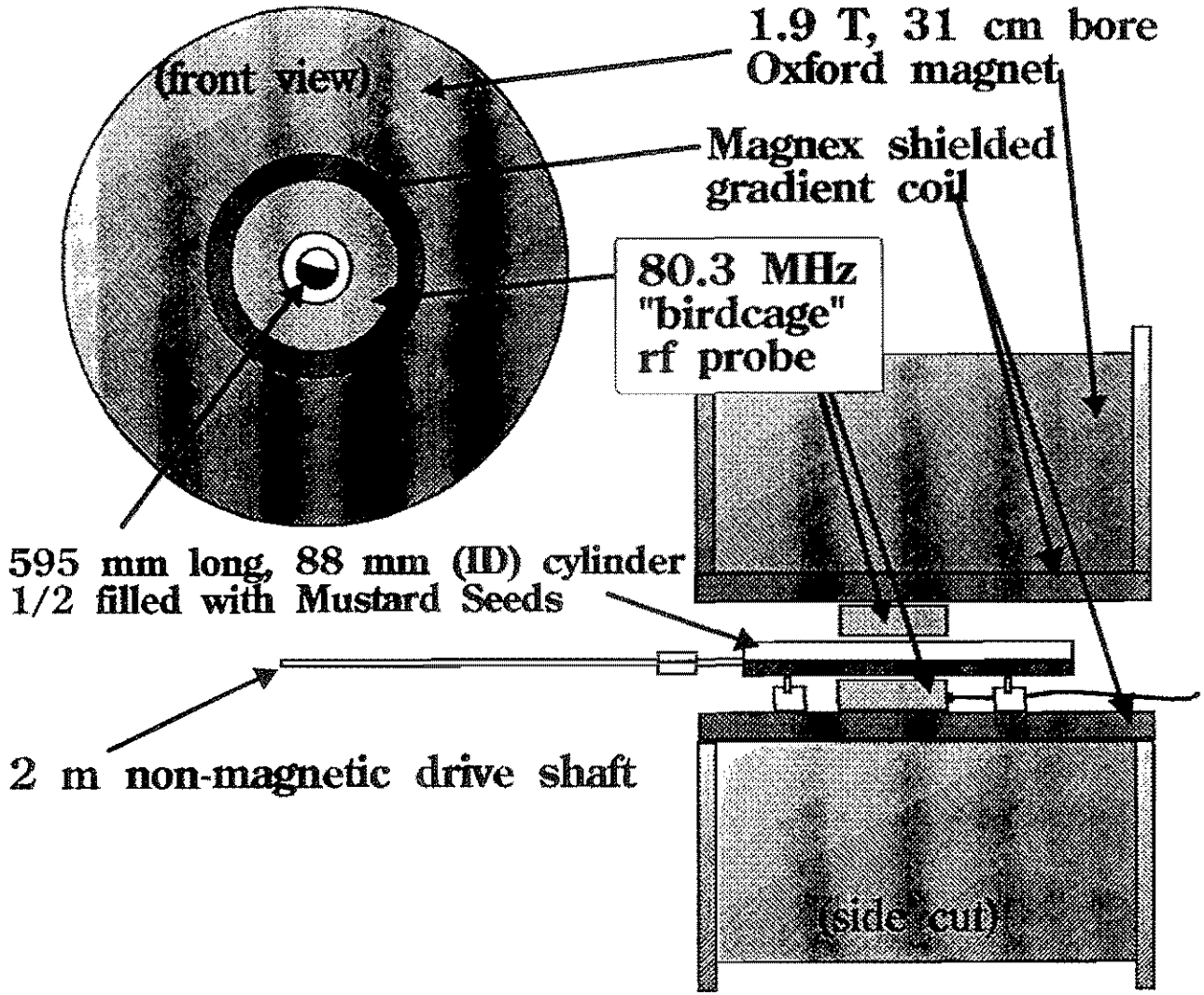
Corrective measures

- Liners
- Opening
- Vibrators
- Material Properties
  - -- remove fine particles
  - -- drying particles
  - -- adding flow-promoting substances
  - -- adding cohesiveness (eliminate segregation ?)

D.F. Bagster 1983

- Stablize the code
- Complete "mini hopper" ⟶ MRI
- Improve { plunger design.
  partitioned bin design




(front view)
1.9 T, 31 cm bore
Oxford magnet
Magnex shielded
gradient coil
80.3 MHz
"birdcage"
rf probe
595 mm long, 88 mm (ID) cylinder
1/2 filled with Mustard Seeds
2 m non-magnetic drive shaft
(side cut)

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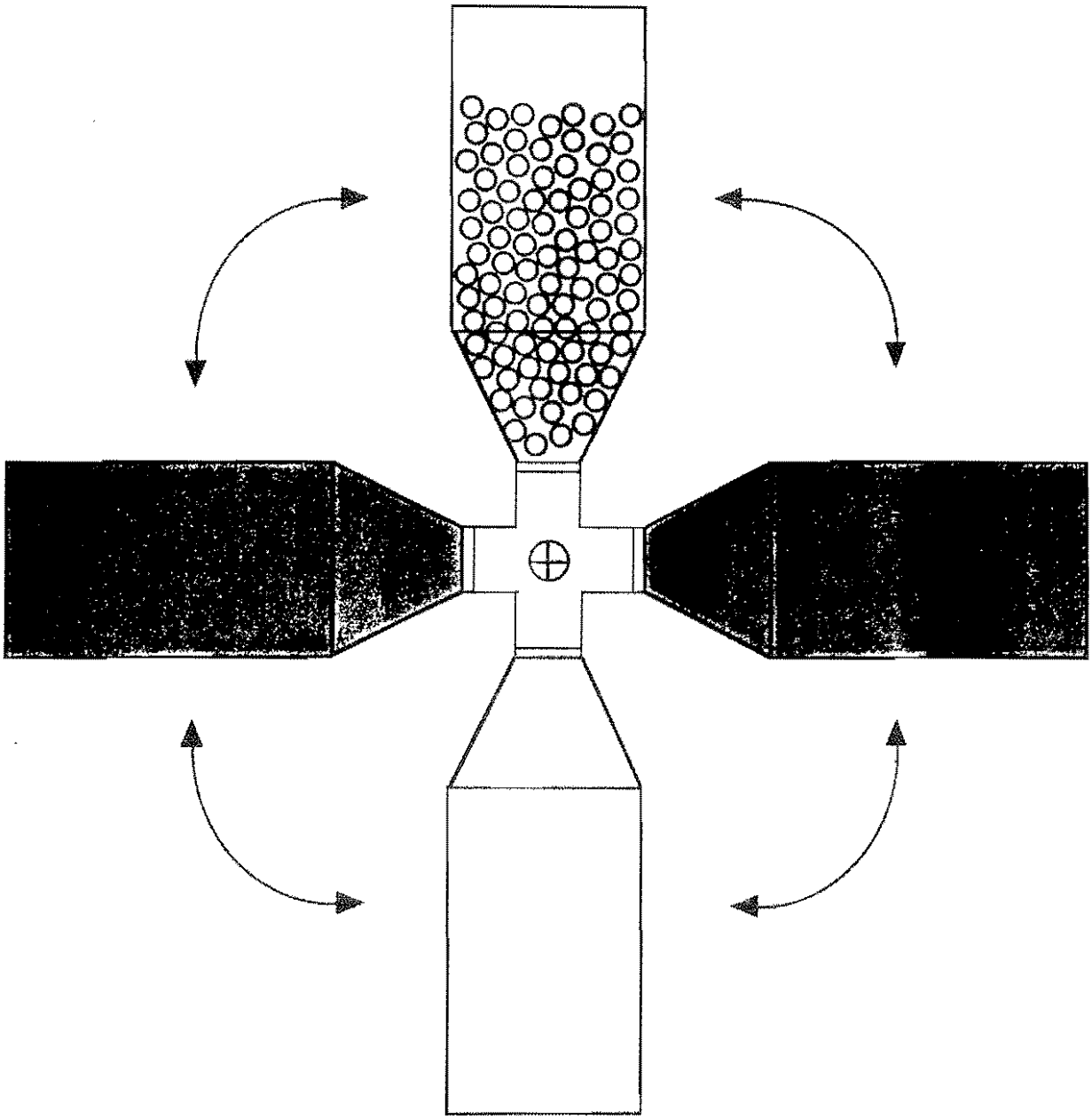


Los Alamos
NATIONAL LABORATORY

OVERVIEW OF THE SERDP/CAME PROGRAM

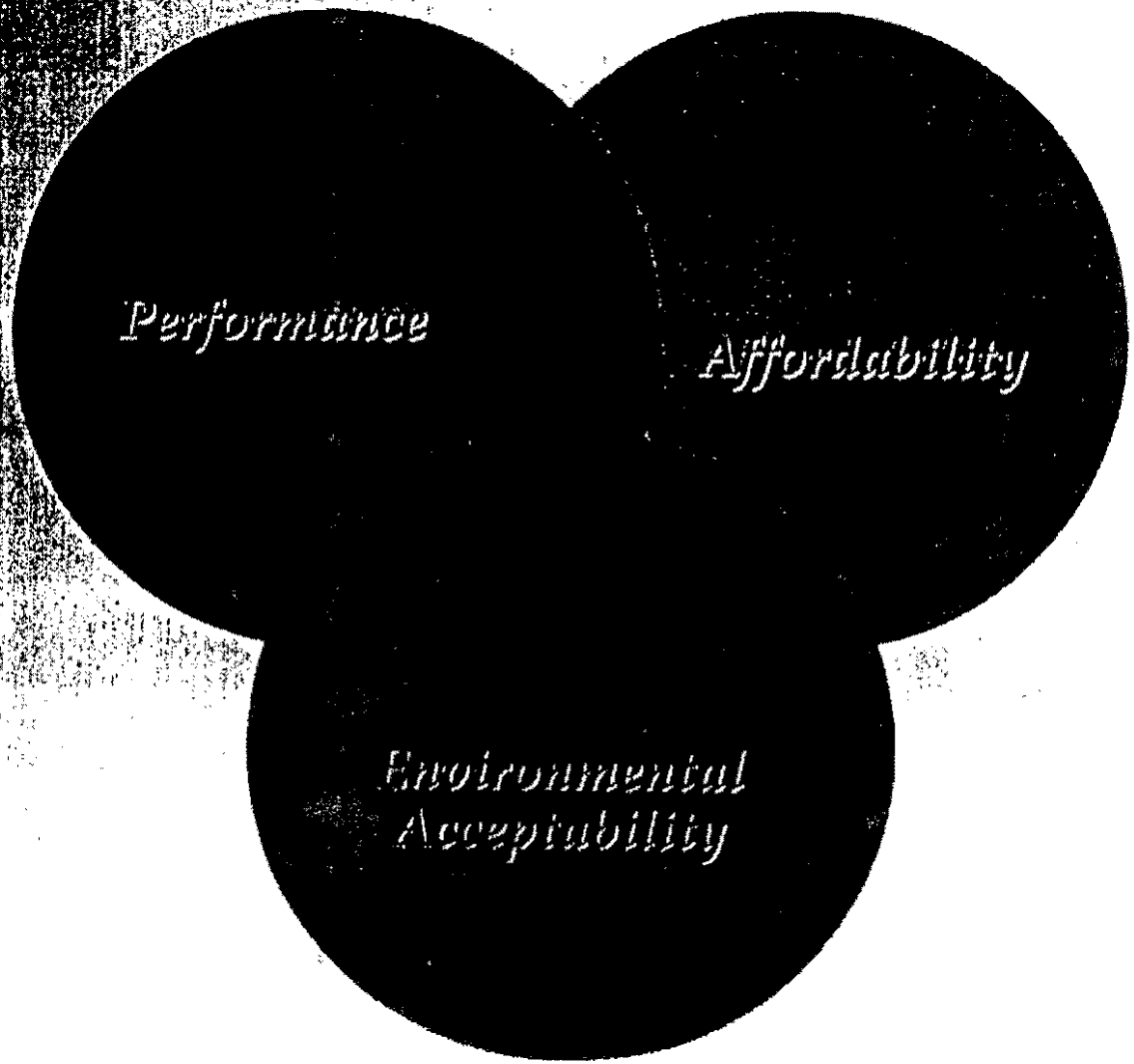
A Joint DOD/DOE Program for the
Clean, Agile, Manufacture of Energetics

Kirk Newman
NSWC, Indian Head Division
Research and Technology Department (Code 9311)

Sandia National Laboratories

NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

Make Environmental Security an Integral Element of Acquisition Decision Making



STRATEGIC ENVIRONMENTAL RESEARCH & DEVELOPMENT PROGRAM

OUTLINE OF TALK:

[1] MATERIAL BALANCE DATA FOR LIFE CYCLE POLLUTION ASSESSMENT

[2] DISCUSSION OF LEVERAGING OPPORTUNITIES

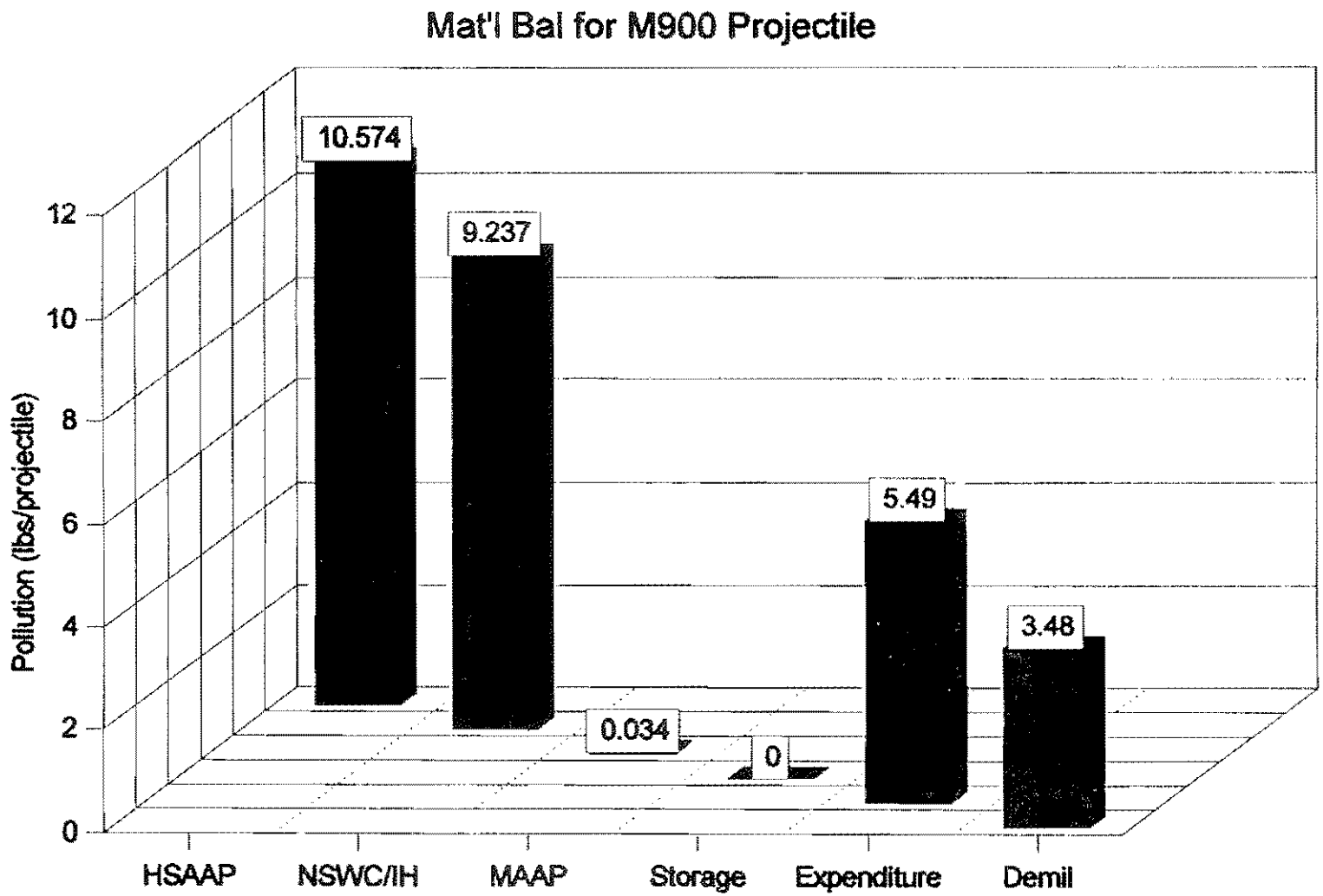
[3] APPLICATION OF COMPUTATIONAL TOOLS FOR BLU-97 SUBMUNITION REJECTION RATE

[4] APPLICATION OF COMPUTATIONAL TOOLS FOR TPE PBX DEMONSTRATION

[5] CONCLUSIONS

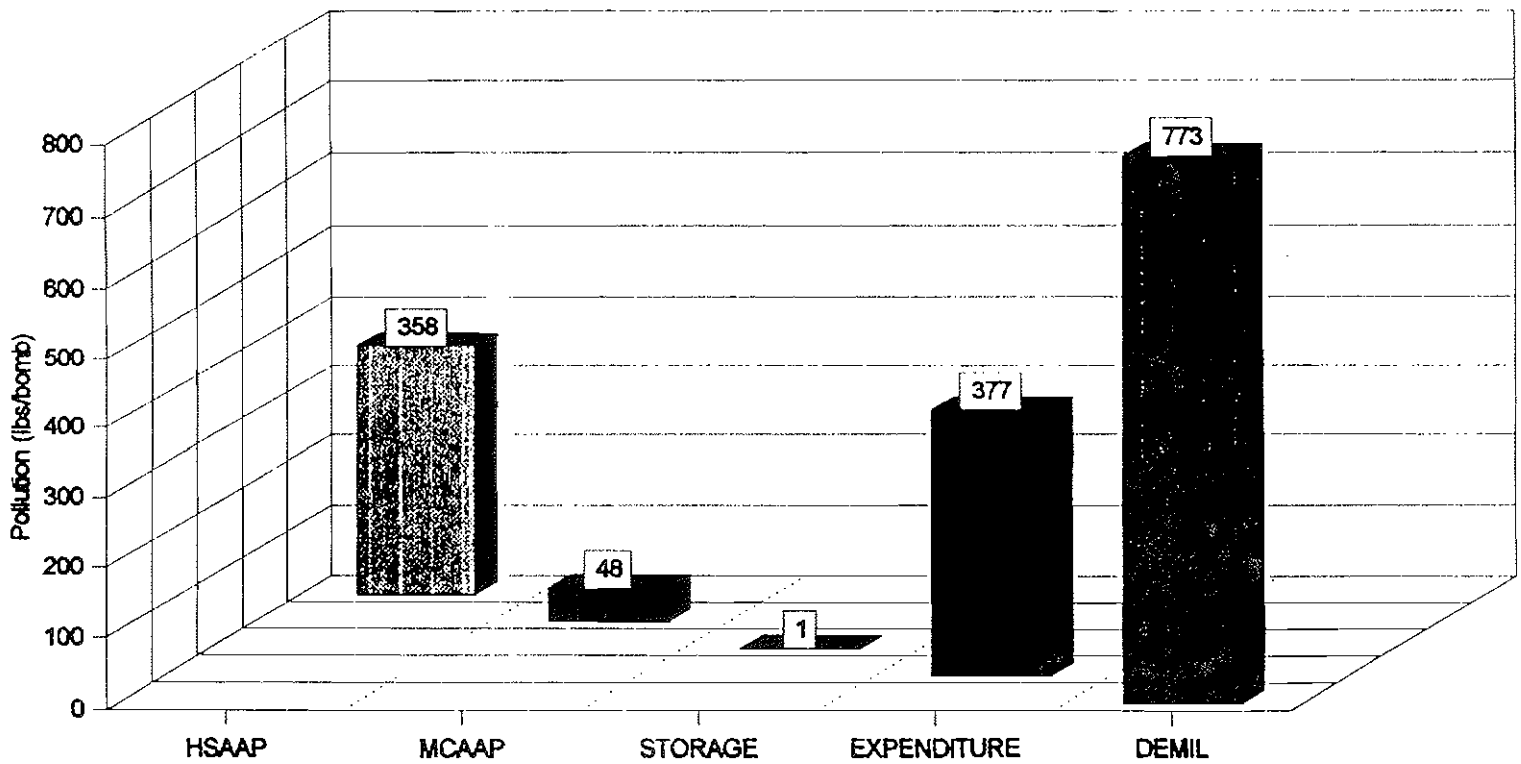
NSWC
Naval Surface Warfare Center
INDIAN H[illegible]IVISION

Life Cycle Data Collection



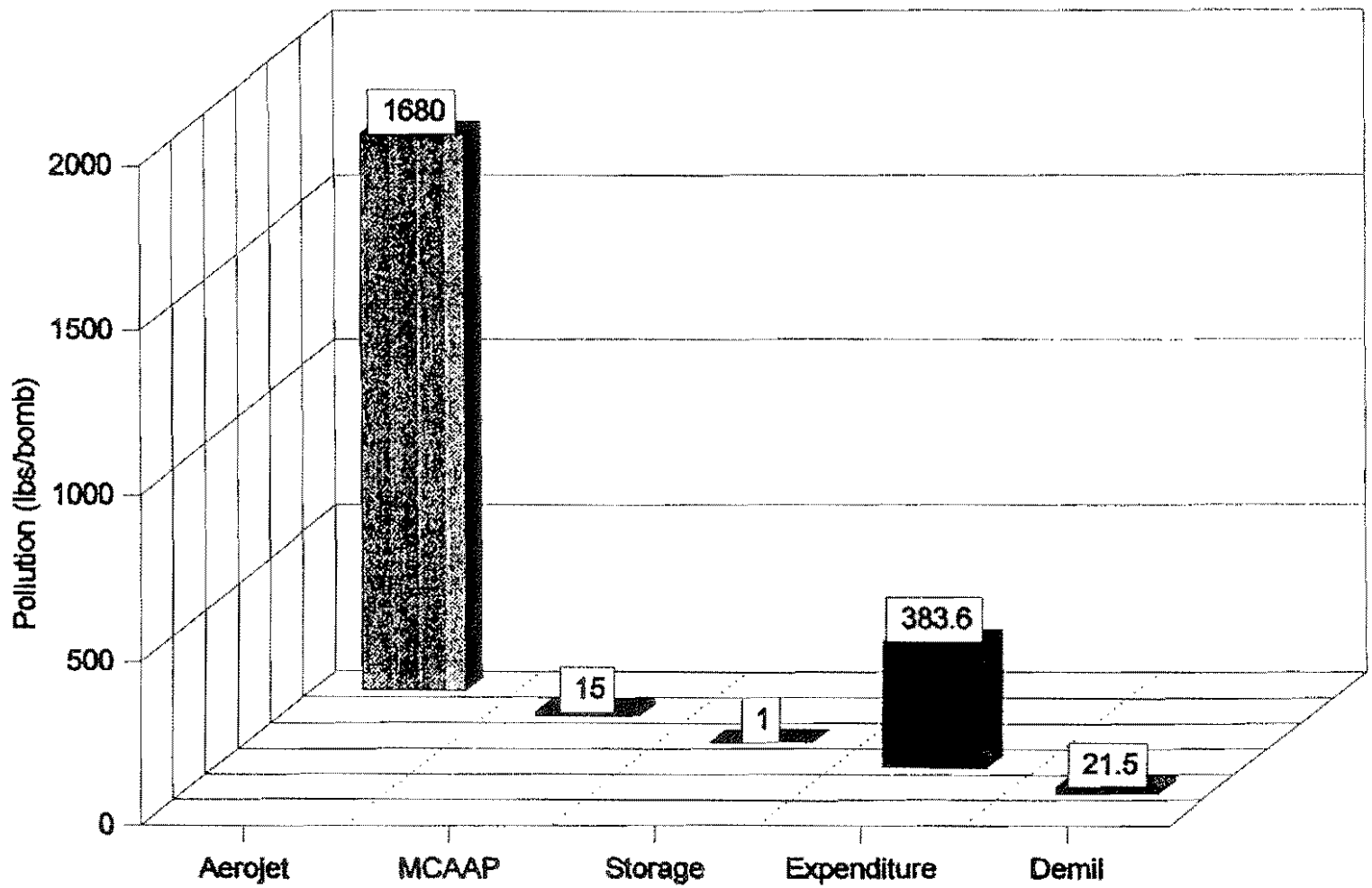
Life Cycle Data Collection

Mat'l Bal for GBU-24B/B Penetrator Bomb



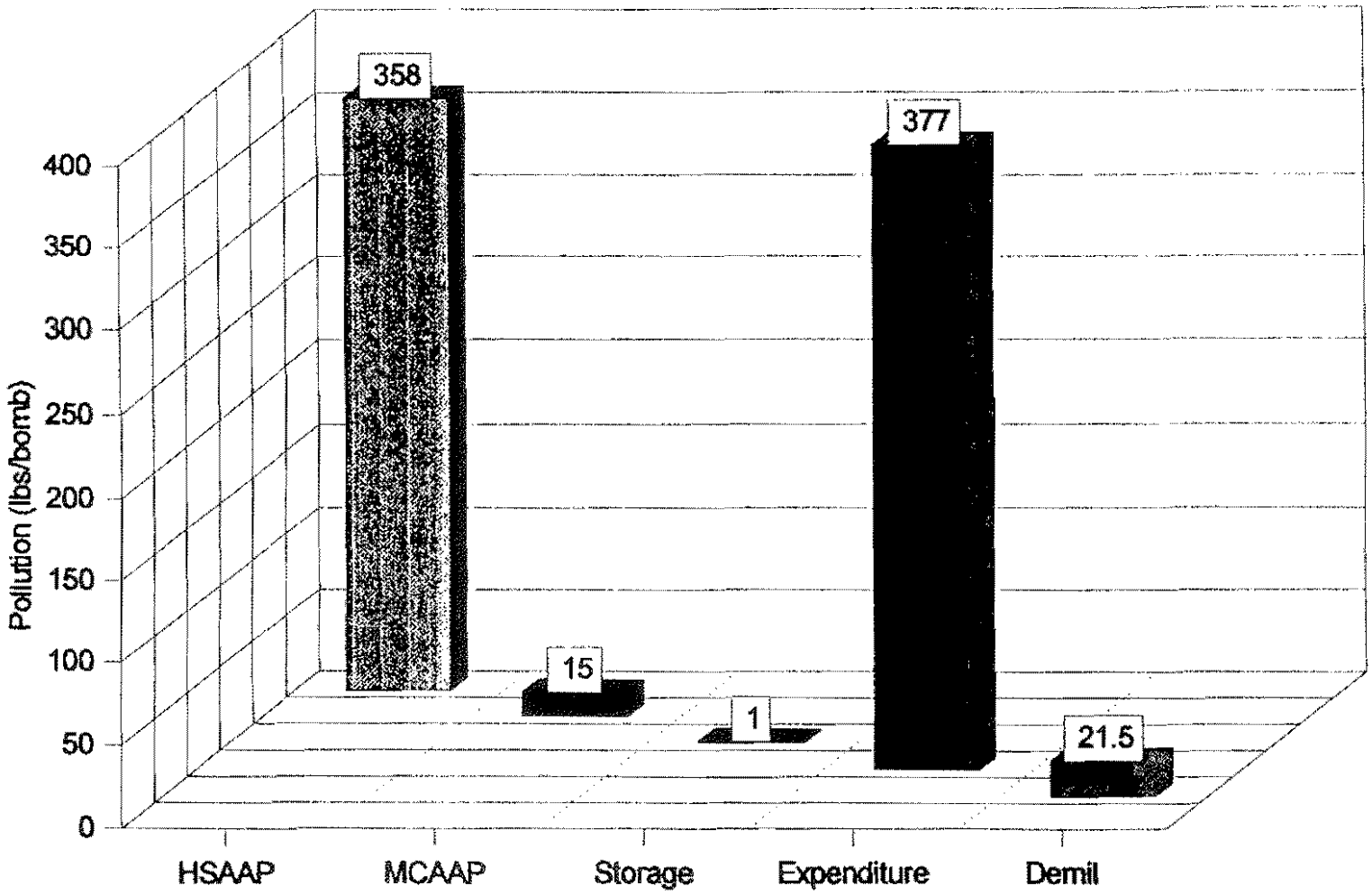
Life Cycle Data Projection for TNAZ/AL

Mat'l Bal for GBU-24 Penetrator Bomb



Life Cycle Data Projection for TPE/PBX

Mat'l Bal for GBU-24 Penetrator Bomb



CAMPEP: TECHNOLOGY ASSESSMENT

[1] HOW CAN PROCESSING BE RESPONSIBLE FOR A LARGE PORTION OF LIFE CYCLE WASTES ?

[2] WHAT ARE THE ENERGETIC MATERIAL CHARACTERISTICS THAT ADVERSELY AFFECT PRODUCT QUALITY ?

[3] WHAT PROCESS CONTROL PARAMETERS NEED IMPROVEMENT TO ACHIEVE A REDUCED SCRAP RATE ?

CAMPEP: TECHNOLOGY ASSESSMENT

[4] WHAT KIND OF FUNDAMENTAL DATA NEEDS TO BE COLLECTED ? WHO WILL COLLECT IT ? WHICH MATERIALS ARE CHOSEN ?

[5] HOW WILL THIS DATA BE USED ? WHO WILL USE IT ?

[6] IS THE SERDP/CAMPEP GOAL OF POLLUTION REDUCTION ACHIEVED ?

[7] HAVE WE DELIVERED SOMETHING OF VALUE TO LEVERAGED PROGRAMS ?

STRATEGIC ENVIRONMENTAL RESEARCH & DEVELOPMENT PROGRAM

CAMPEP: TECHNOLOGY ASSESSMENT

LEVERAGED PROGRAMS

JOINT STAND OFF WEAPON (JSOW) & TOMAHAWK (CEM)

RHEOLOGY SUPPORT

PROCESS IDENTIFICATION & DEVELOPMENT

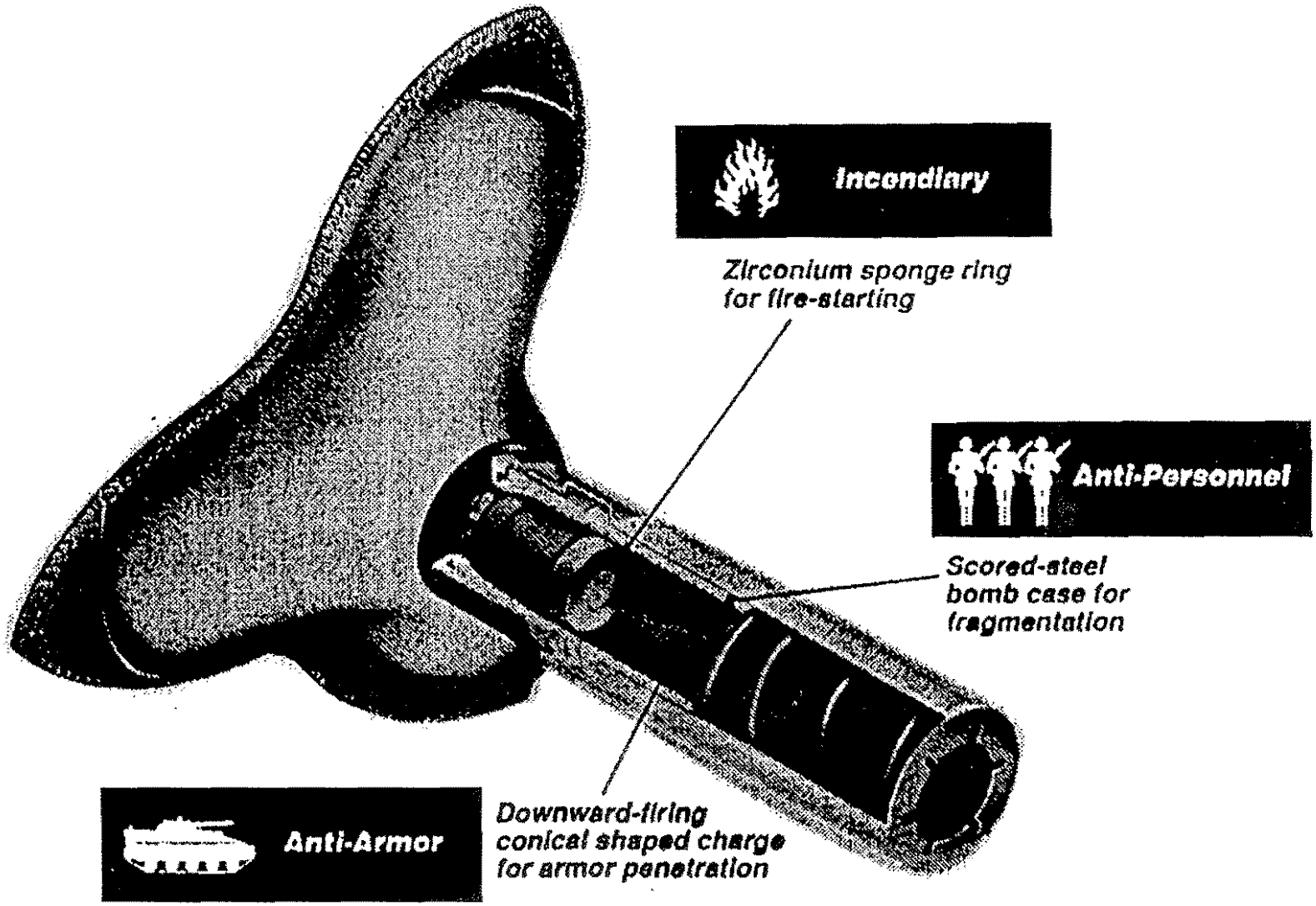
PROCESS CONTROL

NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

DEPARTMENT OF THE NAVY
SEA SYSTEMS COMMAND

AIR DELIVERED WEAPONS

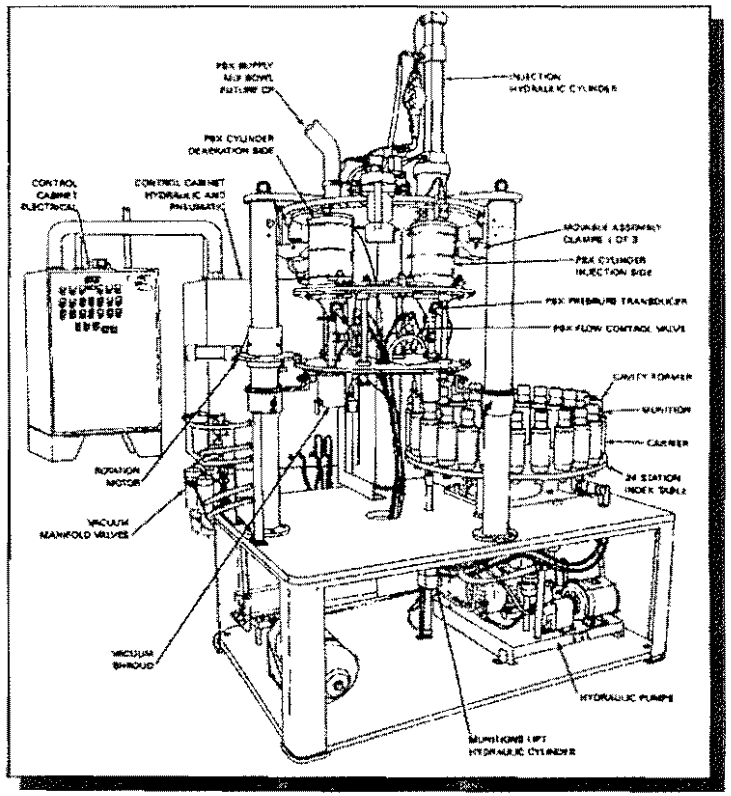
BLU-97 A/B
Combined Effects Bomblet



CAMPEP PROCESSING TECHNOLOGY ASSESSMENT

INJECTION LOADING OF BLU-97 SUBMUNITIONS

- *Joint Stand-Off Weapon (JSOW) has loaded 2,448 BLU-97 submunitions with PBXN-107 having an average reject rate of about 24% using a volumetric loader. The problems are due to particle jamming and binder filtration, as well as the geometry of the volumetric loader.*
- *TOMAHAWK Combined Effects Munition (CEM) is also planning to procure PBXN-107 loaded BLU-97 submunitions.*
- *Selection of an injection loading process with model-based and rule-based process control can resolve these processing problems. Resources include NSWC, NAWC, LANL, SNL, MIT, SIT, and Cal Tech.*



NSWC Injection Loading Apparatus

Naval Surface Warfare Center
INDIAN HEAD DIVISION

STRATEGIC ENVIRONMENTAL RESEARCH & DEVELOPMENT PROGRAM

CAMPEP PROCESSING TECHNOLOGY ASSESSMENT

JSOW and their EM&D contractor recognized that the low viscosity of the polyacrylate binder in PBXN-107 was causing particle jamming and binder filtration problems. Their approach was to pre-polymerize the binder to increase the viscosity. However, the chemical reaction kinetics of the free-radical polymerization do not yield a reproducible viscosity.

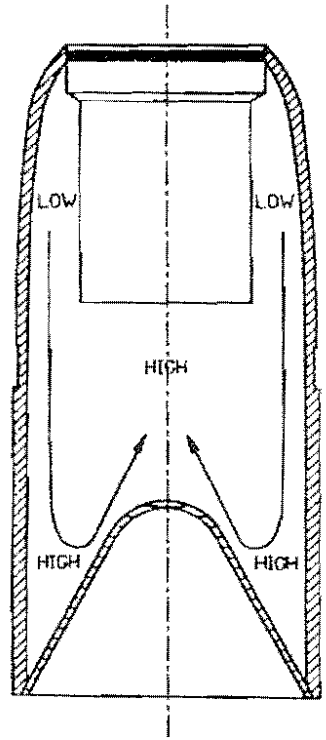
According to the DCMO and ISEA, the processing problems associated with loading PBXN-107 into BLU-97 submunitions include [a] voids, [b] fill height, and [c] density and RDX gradients.

The SERDP/CAMPEP review of BLU-97 loading data for indicates the following causes:

[a] The quad-modal particle size distribution of RDX in PBXN-107 is not well controlled. PBXN-107 has four classes of RDX having average particle sizes of 25, 200, 300, and 900 microns. Momentum and mass transport problems such as flow instabilities, shear induced particle migration, particle jamming, and binder filtration occur when flowing through narrow channels and corner turning.

[b] The EM&D contractor uses process geometry having five 90 degree turns, and is too long (causing OB/OD of 140 lbs of PBXN-107 after each run).

[c] The EM&D contractor uses inadequate process control for momentum and heat transfer (can't control the binder viscosity, and can't prevent the reject from being made).



Relative magnitude of density and RDX gradients in PBXN-107 loaded BLU-97 submunitions

NSWC
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INDIAN HEAD DIVISION

CAMPEP: TECHNOLOGY ASSESSMENT

[3] WHAT PROCESS CONTROL PARAMETERS NEED IMPROVEMENT TO ACHIEVE A REDUCED SCRAP RATE ?

If we are to demonstrate processing and reprocessing of thermoplastic elastomers as legitimate clean binders for explosives and propellants, we need better understanding of what we're measuring so that we can use the data in appropriate control alogoritms. We can measure ΔP, ΔT, η, and ρ. We need to control momentum transport ($Q = f(\Delta P, n, m)$), heat transfer (as it relates to viscosity ($\eta = f(T, \phi)$) and viscous heating (dT/dr and dT/dt)), and mass transfer (as it relates to air removal (ρ) and particle migration (ϕ)). We also need to incorporate new control strategies that anticipate when undesired transport phenomena (e.g., momentum, heat, mass) may occur and take preemptive corrective action.

CAMPEP: TECHNOLOGY ASSESSMENT

PROCESS CONTROL ELEMENTS - JSOW & TOMAHAWK (PBXN-107)

[a] The viscosity of PBXN-107 behaves in a predictable manner when the thermal load is decreased so that the temperature dependency of the binder is dominant over the chemical reaction kinetics. The viscosity increases as temperature decreases.

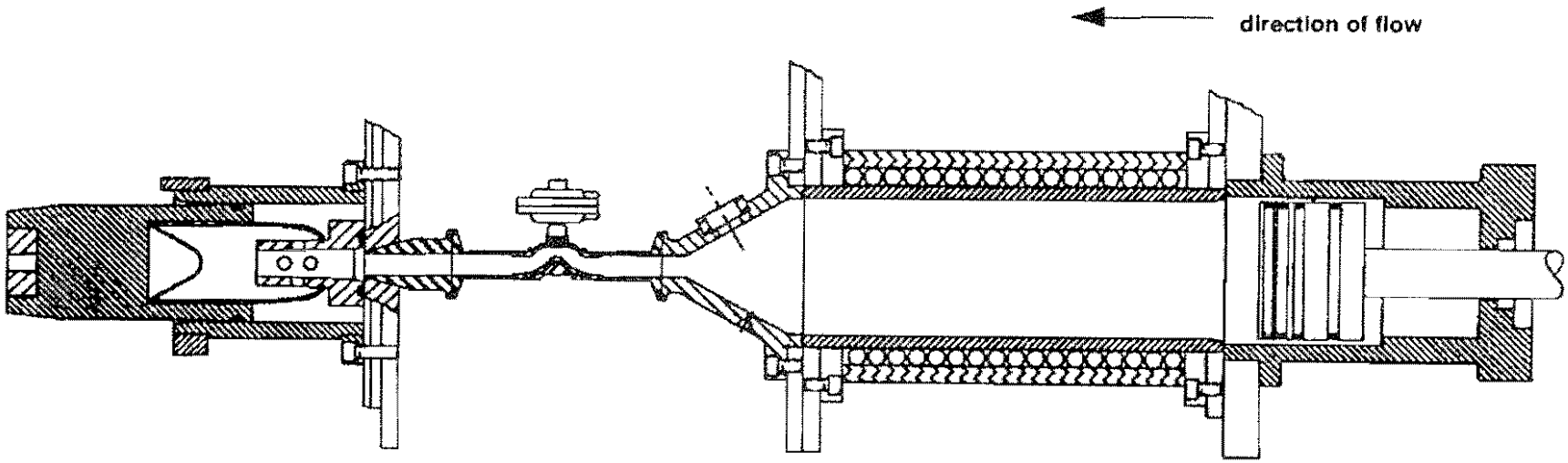
$$\eta = A \exp(E/RT)$$

[b] Priority of process control strategy is for (1) Arrhenius heat transfer model, (2) Phillips mass transfer model from computational fluid dynamics, and then (3) momentum transport rules derived from (i) Power Law equation (or Herschel-Bulkley equation) using rheological data, and (ii) expert operator experience.

STRATEGIC ENVIRONMENTAL RESEARCH & DEVELOPMENT PROGRAM

CAMPEP PROCESSING TECHNOLOGY ASSESSMENT

The mock injection loading NMRI experiments performed at SNL and LMSC are based upon the NSWCIHD injection loader geometry to determine where flow instabilities occur when processing PBXN-107. This pilot plant apparatus represents simplified process geometry. There are no 90 degree turns, no long length of plumbing, and the smallest flow channel is in the 1/2 inch diaphram valve.



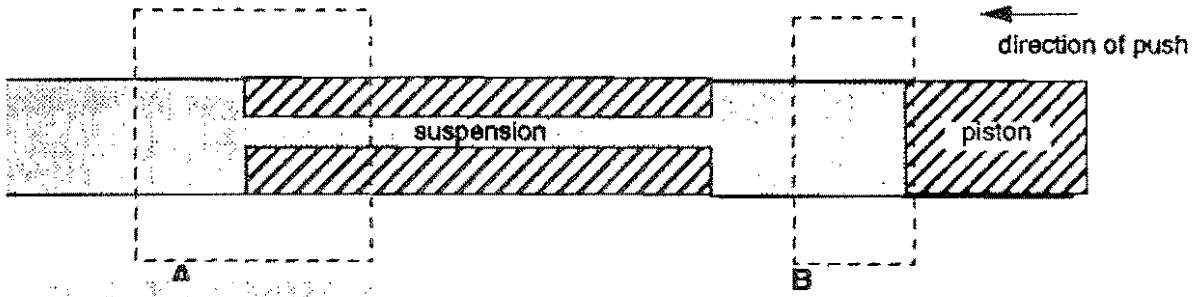
FLOW GEOMETRY IN THE NSWCIHD INJECTION LOADER

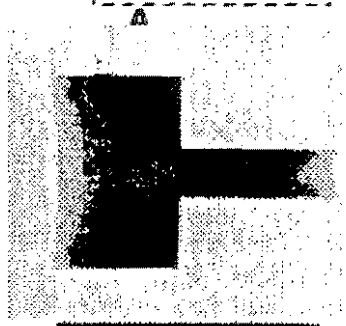
NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

MRI of Injection Loading Reveals Flow-Induced Inhomogeneities

A piston pushes a concentrated suspension at a slow steady rate through a contraction, a straight section of piping, and an expansion to simulate the performance of the injection loading of bomblets.

Results indicate the need to do follow-up experiments in a more detailed model of the injection loader and with better simulants





A

Particles migrate toward the small pipe axis creating a zone of higher binder content near the walls (high particle content along axis).

Particles are swept out of "corners" of the expansion creating zones of high binder content here, too.

B

A binder-rich region appears at the face of the piston and along the axis of the larger pipe.
This region is convected into the contraction as the piston moves.

Potential for inhomogeneities in final product

STAGES OF MOLD-FILLING PROCESS

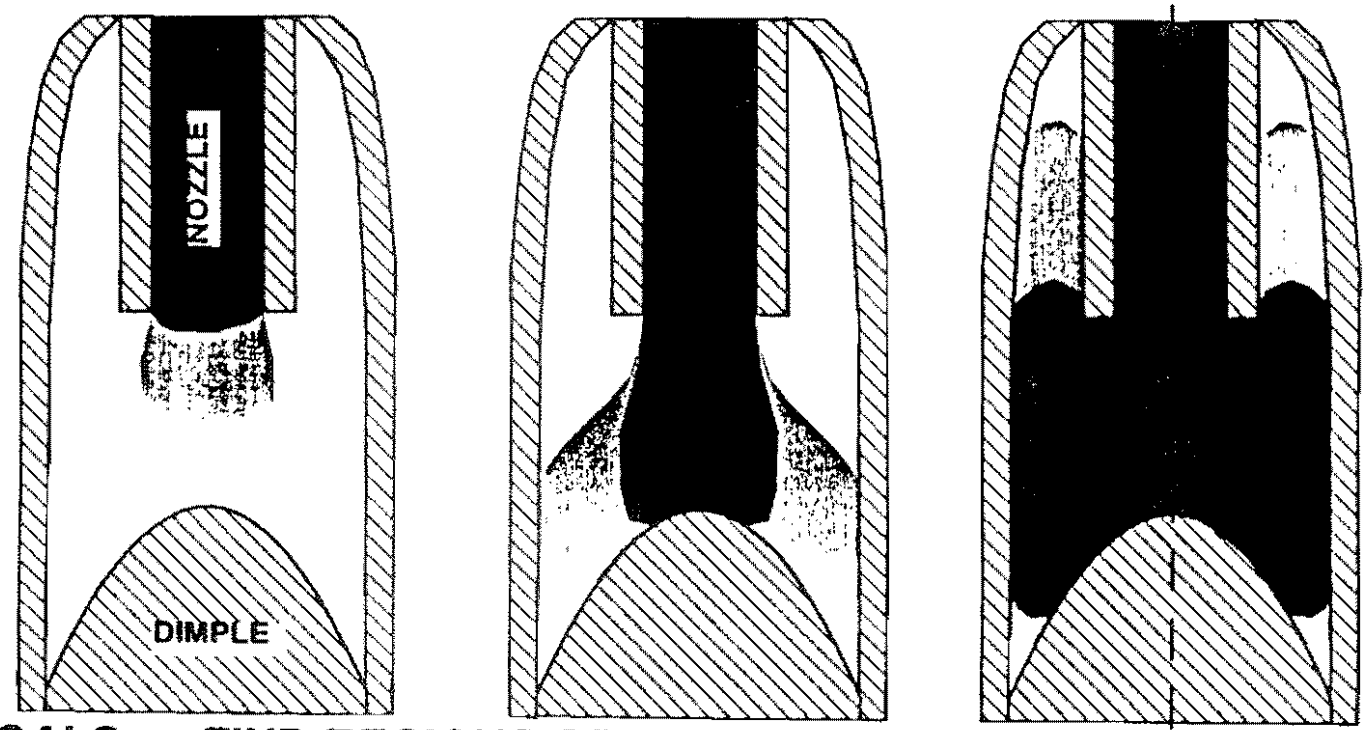
Sandia National Laboratories

Engineering Sciences Center

EXTRUSION FROM NOZZLE

FLOW OVER DIMPLE AND UP WALL

FILLING OF CORNERS



GOALS: *FIND REGIONS OF HIGHEST SHEAR*

DETERMINE FLOW STRUCTURE

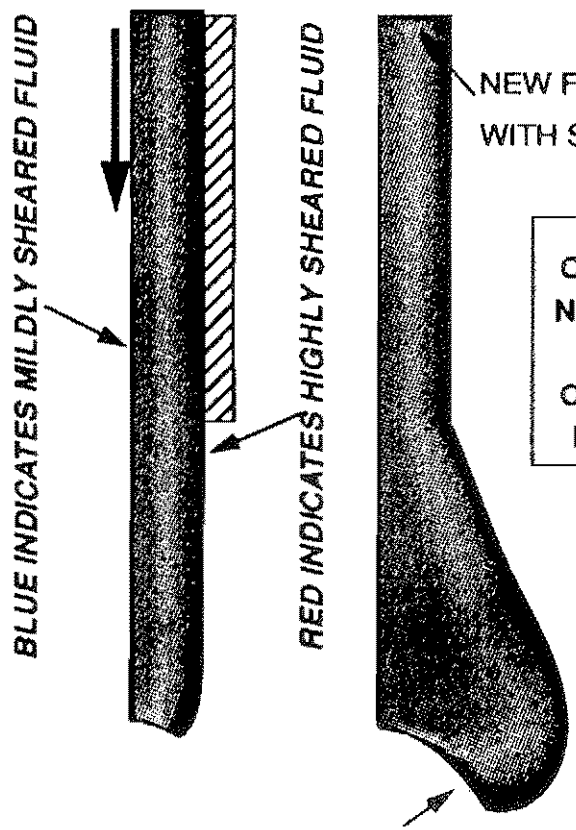
FOLLOW HISTORY OF HIGHLY SHEARED FLUID

STREAKLINES OF SHEARED FLUID

Sandia National Laboratories

Engineering Sciences Center

MARK INITIAL FLUID POSITION WITH VARYING CONCENTRATIONS OF TRACER SPECIES (WHICH DOES NOT DIFFUSE)



ALL RED FLUID ORIGINATES NEAR NOZZLE WALL, ALL BLUE FLUID ORIGINATES NEAR NOZZLE CENTER

ROLLING MOTION OVER DIMPLE TRAPS A LAYER OF HIGHLY SHEARED FLUID

CORE OF MILDLY SHEARED FLUID WITH OUTER LAYER OF HIGHLY SHEARED FLUID, CORNER FILLED WITH HIGHLY SHEARED

Various models exist to predict particle migration

- Phillips *et al.*
  - migration is shear rate induced, particles migrate away from regions of high shear rate.
- McTigue and Jenkins / Nott and Brady
  - migration is induced by particle velocity fluctuations, or 'temperature', with particles migrating towards regions of lower temperature.

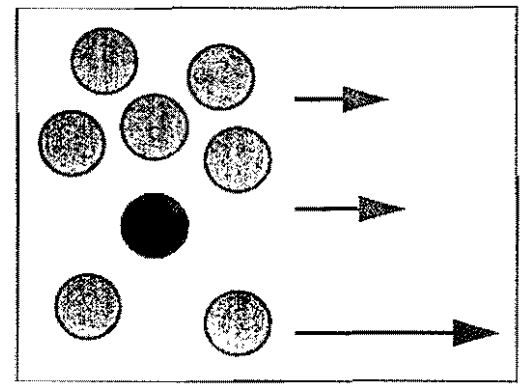
We aim to find the optimal model for particle migration.

- **Our intent:**
  - to predict the evolution of ϕ and v profiles in a number of viscometric flows, using these theories. In this study, we focus on the Phillips model.
  - to compare these predictions to rheological and NMR data.
- **Our objective:**
  - to provide a rational basis to referee between competing models and establish an experimental basis for testing future modifications of existing theories, and new theories.

The Phillips model balances collision and viscosity gradient driven migration.

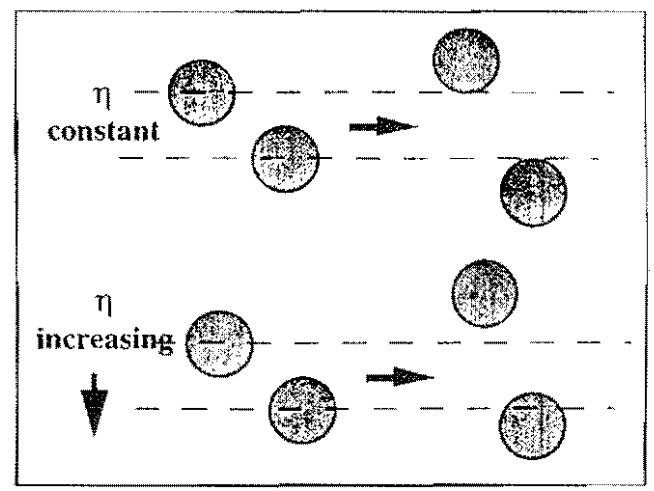
- **Collision term**
  - a particle in a shear field experiences collisions proportional to the relative velocity and to the number of particles, leading to the particle flux expression:

$$N_c = -K_c a^2 \left[\phi \nabla (\dot{\gamma} \phi) \right]$$



- **Viscosity term**
  - particles experience more difficulty in moving towards a higher viscosity region, leading to:

$$N_\eta = -K_\eta \dot{\gamma} \phi^2 \frac{a^2}{\eta} \frac{\partial \eta}{\partial \phi} \nabla \phi$$



Three coupled equations must be solved simultaneously to predict ϕ and v.

- **Particle conservation**

$$\frac{D\phi}{Dt} = a^2 K_c \nabla \cdot \left[\phi \nabla(\dot{\gamma}\phi)\right] + a^2 K_\eta \nabla \cdot \left(\frac{\dot{\gamma}\phi^2}{\eta}\frac{\partial \eta}{\partial \phi}\nabla \phi\right)$$

- **mass conservation**

$$\nabla \cdot v = 0$$

- **momentum conservation**

$$\nabla \cdot \tau + \nabla p = 0$$

$$\mathbf{D} = \frac{1}{2}\left(\nabla v + \nabla v^T\right)$$

$$\tau = 2\eta \mathbf{D}$$

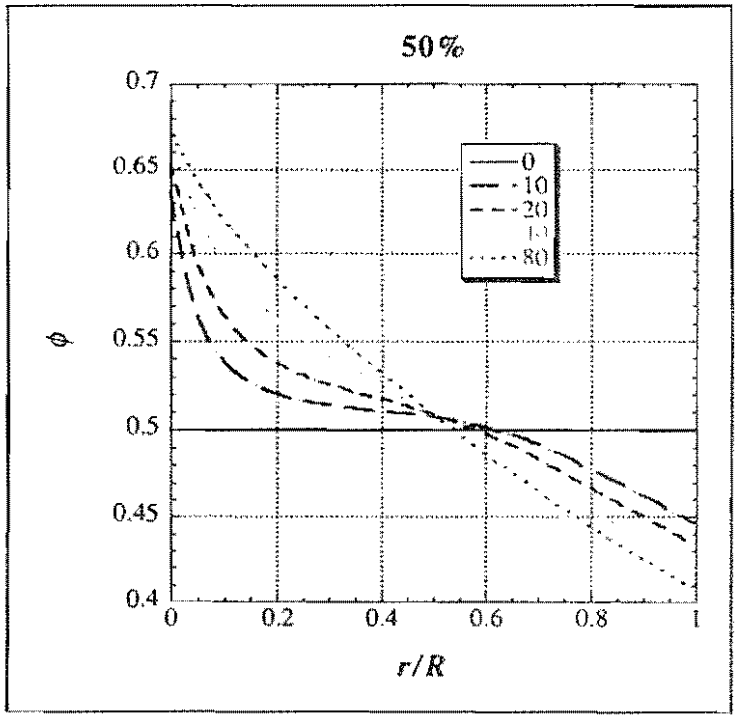
$$\dot{\gamma} = \sqrt{2\,\mathrm{tr}\mathbf{D}^2}$$

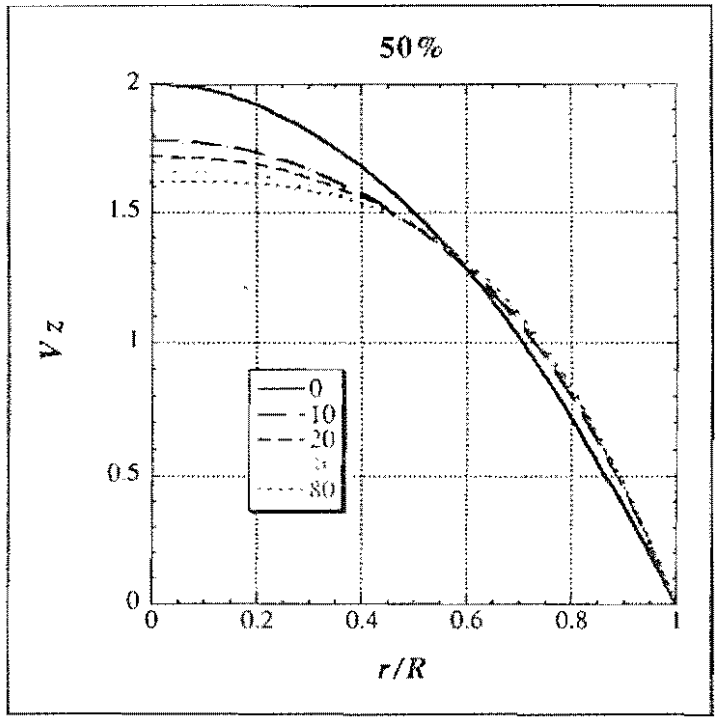
Transient and steady state analysis of viscometric flows:

- Couette
- Parallel plate
- Pipe flow (Poiseuille)

We seek to observe the evolution of concentration and velocity profiles, and the associated torque / pressure drop reductions.
We also develop a quantitative measure of flow development.

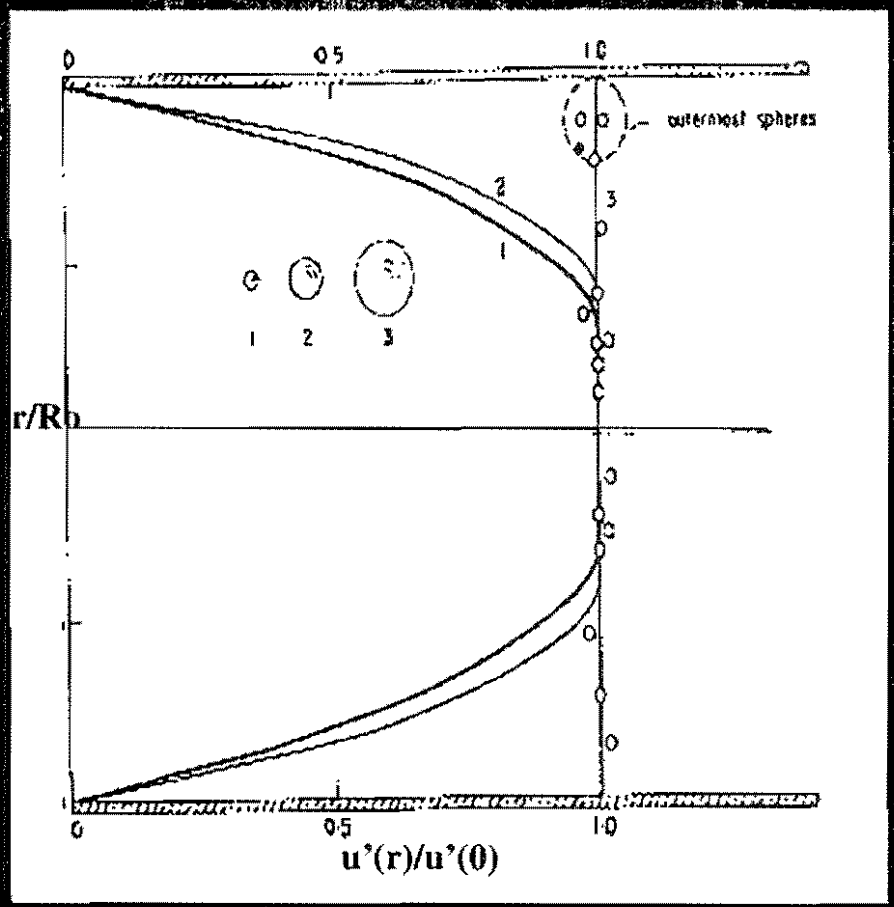
PIPE FLOW - a blunt velocity profile develops very quickly.





As in the Couette flow, velocity profiles approach steady state more quickly than concentration profiles.

Karnis et al. (1966)



Karnis et al. (1966) and Sinton and Chow (1991):

- Observed blunted velocity profiles.
- No "observable" particle migration.

Givler, Altobelli and Fukushima (1991):

- Negatively buoyant suspension.
- Observed significant particle migration and blunting of the velocity profile.

Common Question:

- Where these measurements made at steady state?

We have developed a scalar measure of the extent of demixing.

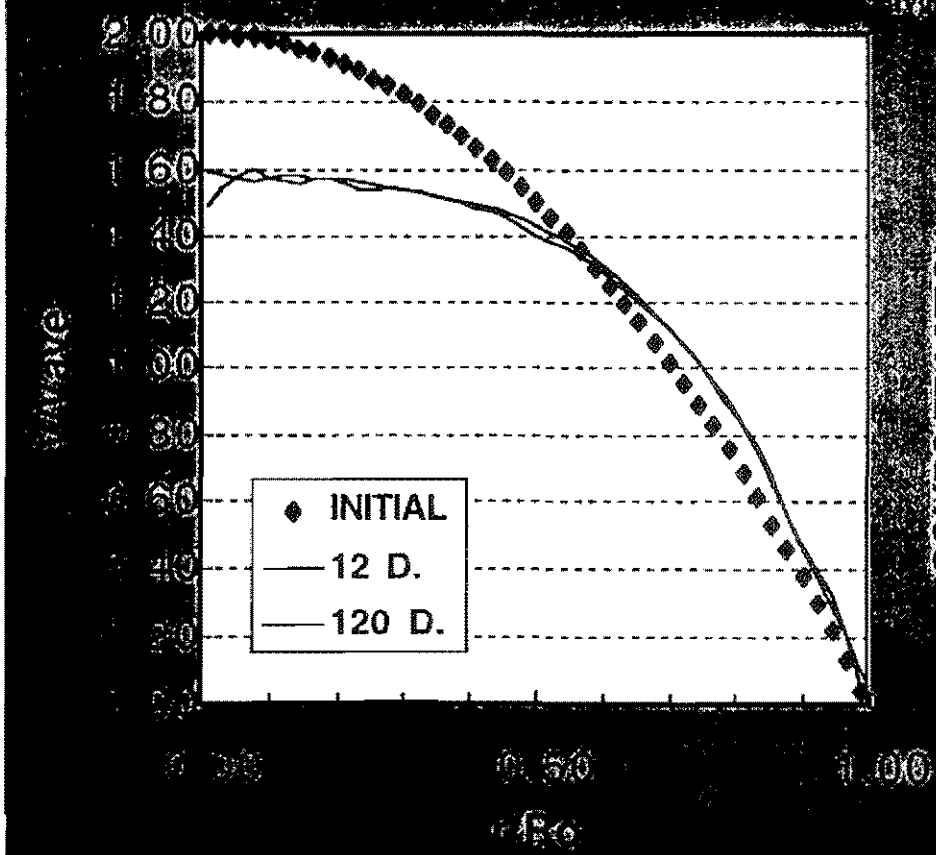
- A parameter which is indicative of the evolution of a profile from with respect to a reference profile, and which is independent of geometry and average particle fraction, can be defined as:

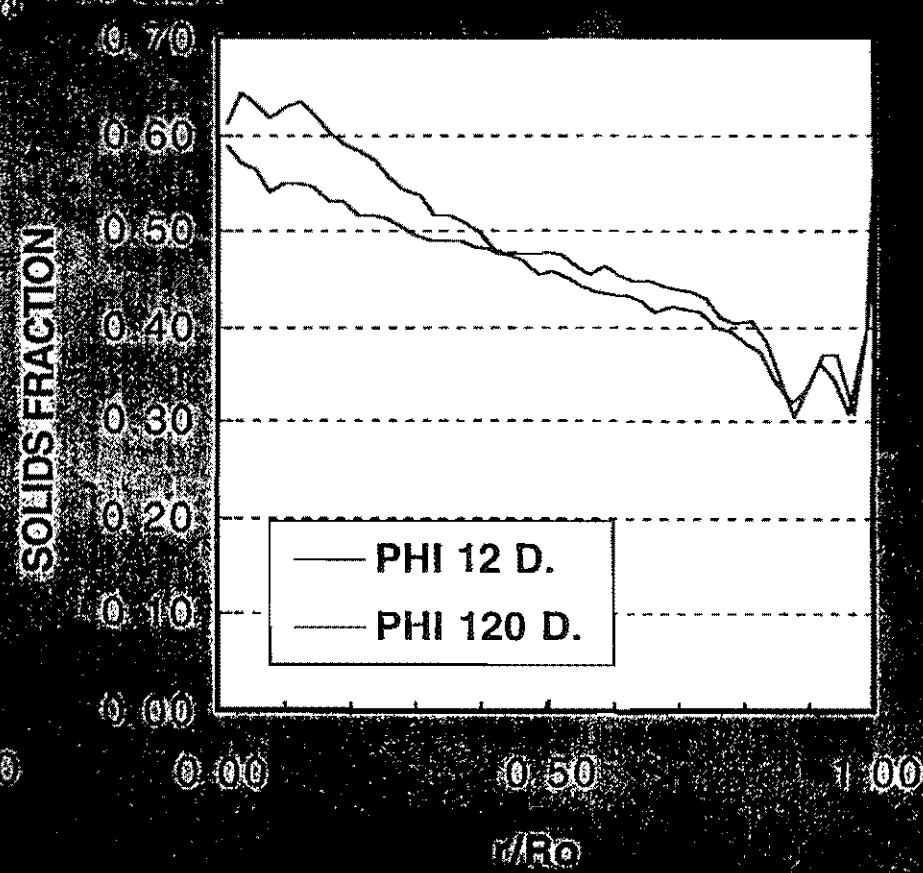
$$D = \frac{1}{A}\int_A \left| \frac{\psi - \psi_{ref}}{\psi_{ave}} \right| dA$$

- the quantity ψ can represent any parameter of interest (concentration, velocity, etc.).

45% SOLIDS CONCENTRATION

$\dot{V}_{avg} = 20$ cm/s

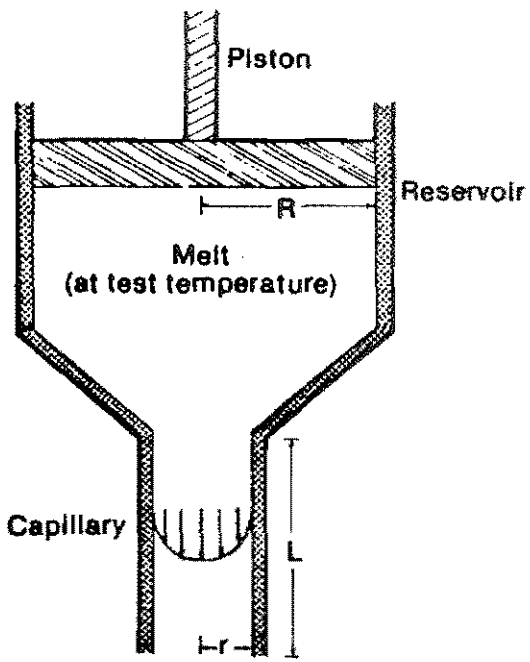




NSWC INDIAN HEAD Calculation Methodology for Shear Behavior of PBX's in the Code 930 Injection Loader Apparatus

The injection cylinder has an inside diameter of 4 inches and is nominally 12 inches from top to bottom. The nomenclature for spreadsheet data is the top of the cylinder is defined as 0 inch, while the bottom is 12 inches. For simplicity, we define R = 2.0 inches, L = 8.5 inches, and r = 0.25 inch.

Capillary tester for volumetric flow rate



Calculating viscosity from flow-rate tests

$$Q = \pi R^2 V \qquad \text{(Eq. 1)}$$

Q = Volumetric flow rate, in.^{3}/sec
R = Piston radius, in.
V = Piston velocity, in./sec

$$\gamma a = \frac{4Q}{\pi r^3} \qquad \text{(Eq. 2)}$$

γa = Apparent shear rate, sec^{-1}
Q = Volumetric flow rate, in.^{3}/sec
r = Capillary radius, in.

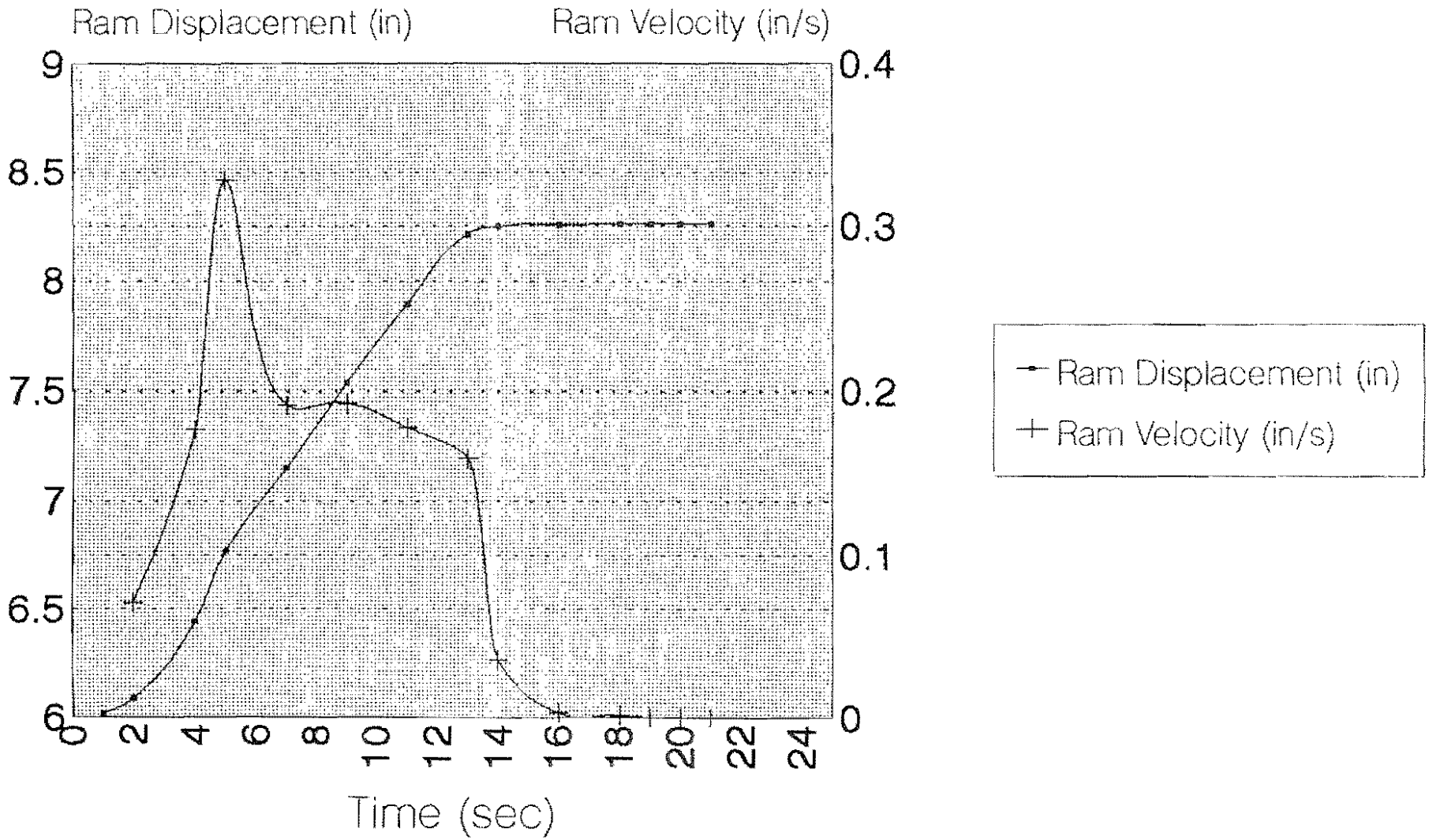
$$\tau = \frac{P \cdot r}{2L} \qquad \text{(Eq. 3)}$$

τ = Shear stress, psi
P = Pressure applied, psi
r = Capillary radius, in.
L = Capillary length, in.

$$\mu = \frac{\tau}{\gamma} \qquad \text{(Eq. 4)}$$

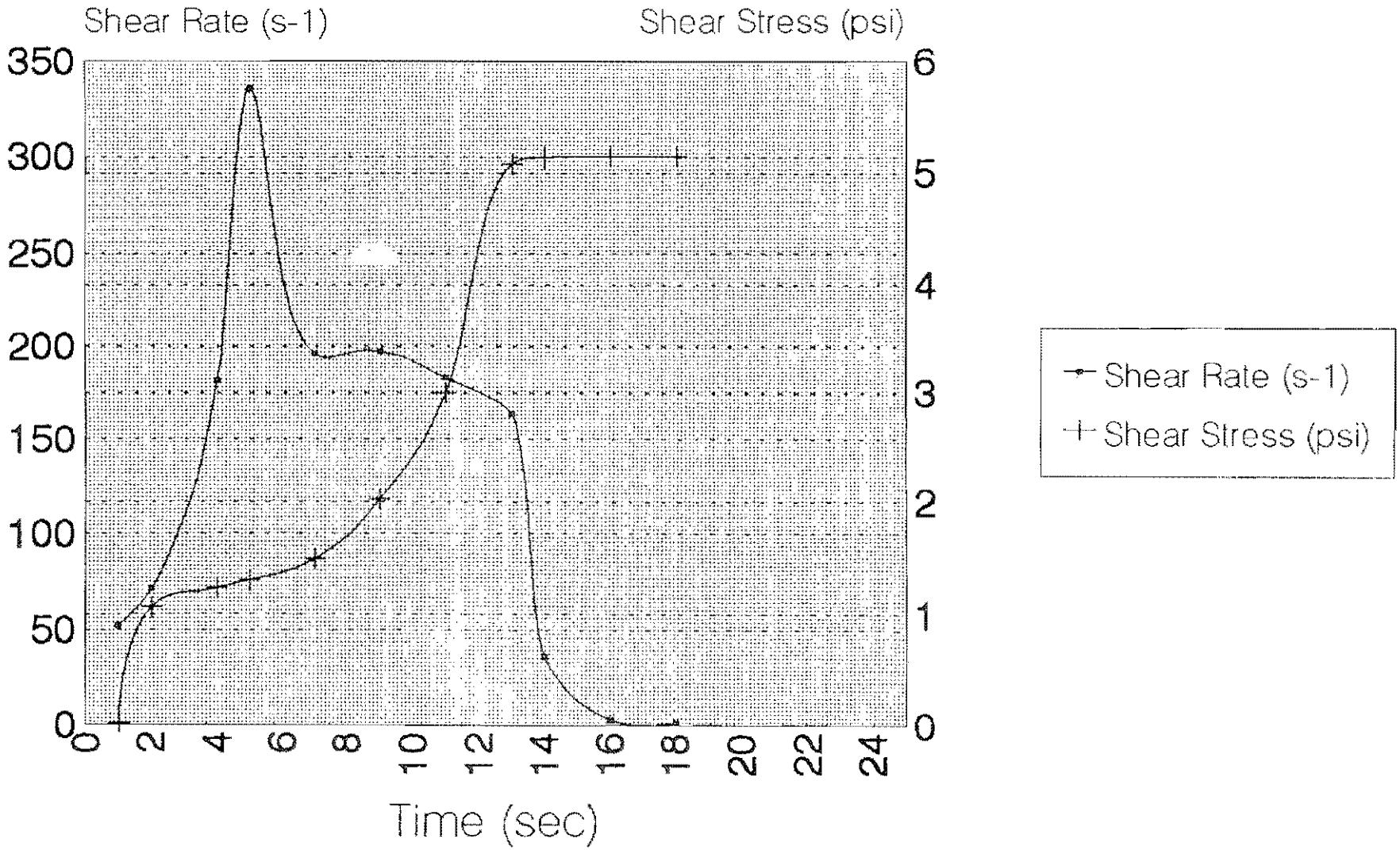
μ = Viscosity, lb-sec/in.^{2}
τ = Shear stress, psi
γ = Apparent shear rate, sec^{-1}

PBXN-107 (loading BLU-97 submunitions)
Ram Displacement and Velocity vs Time

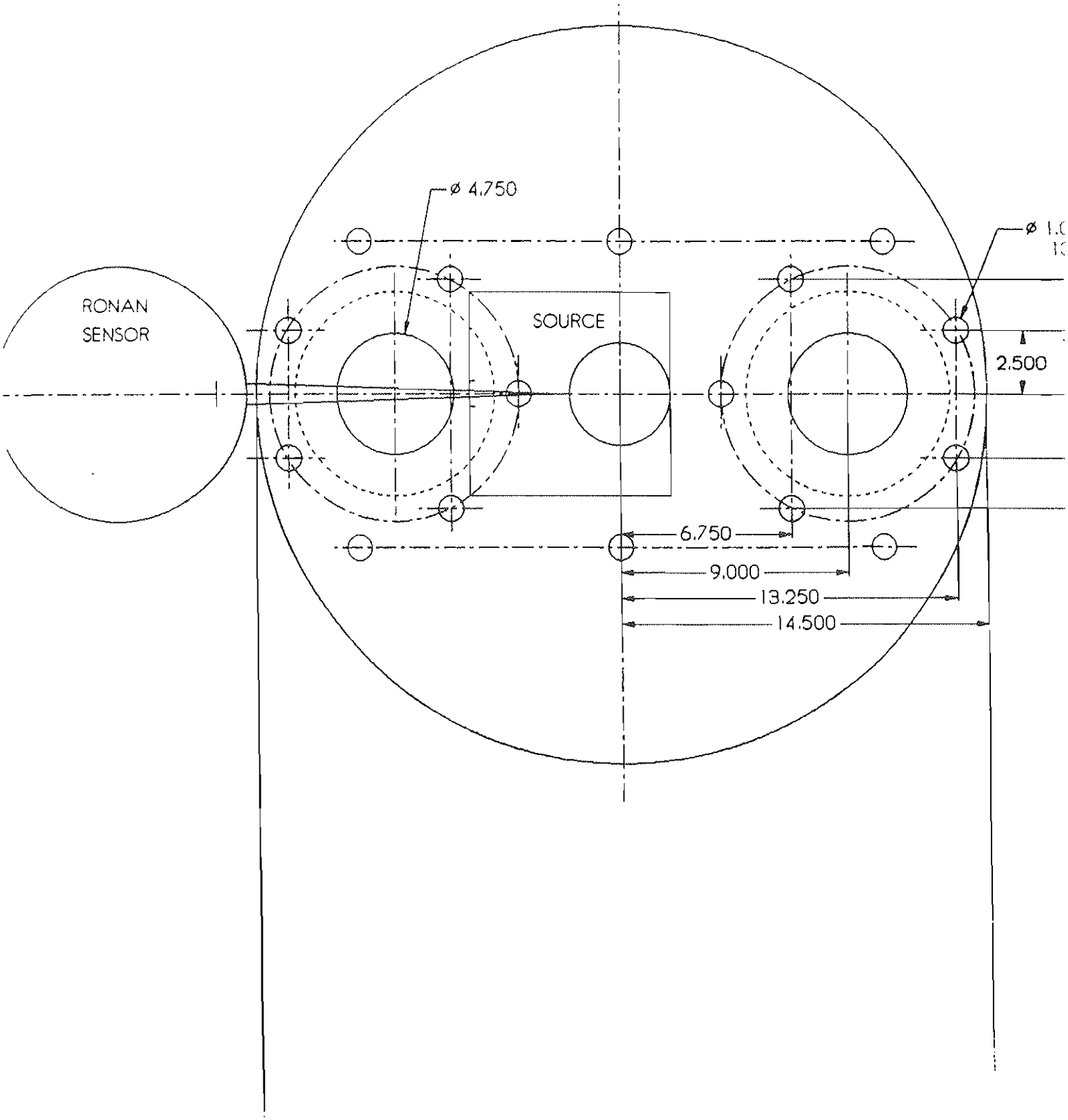


Injection Loading Run 1/22/93 (Increment #3)

PBXN-107 (loading BLU-97 submunitions)
Shear Rate and Shear Stress vs Time



Injecti Loading Run 1/22/93 (Increment #3)


ø 4.750
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RONAN
SENSOR
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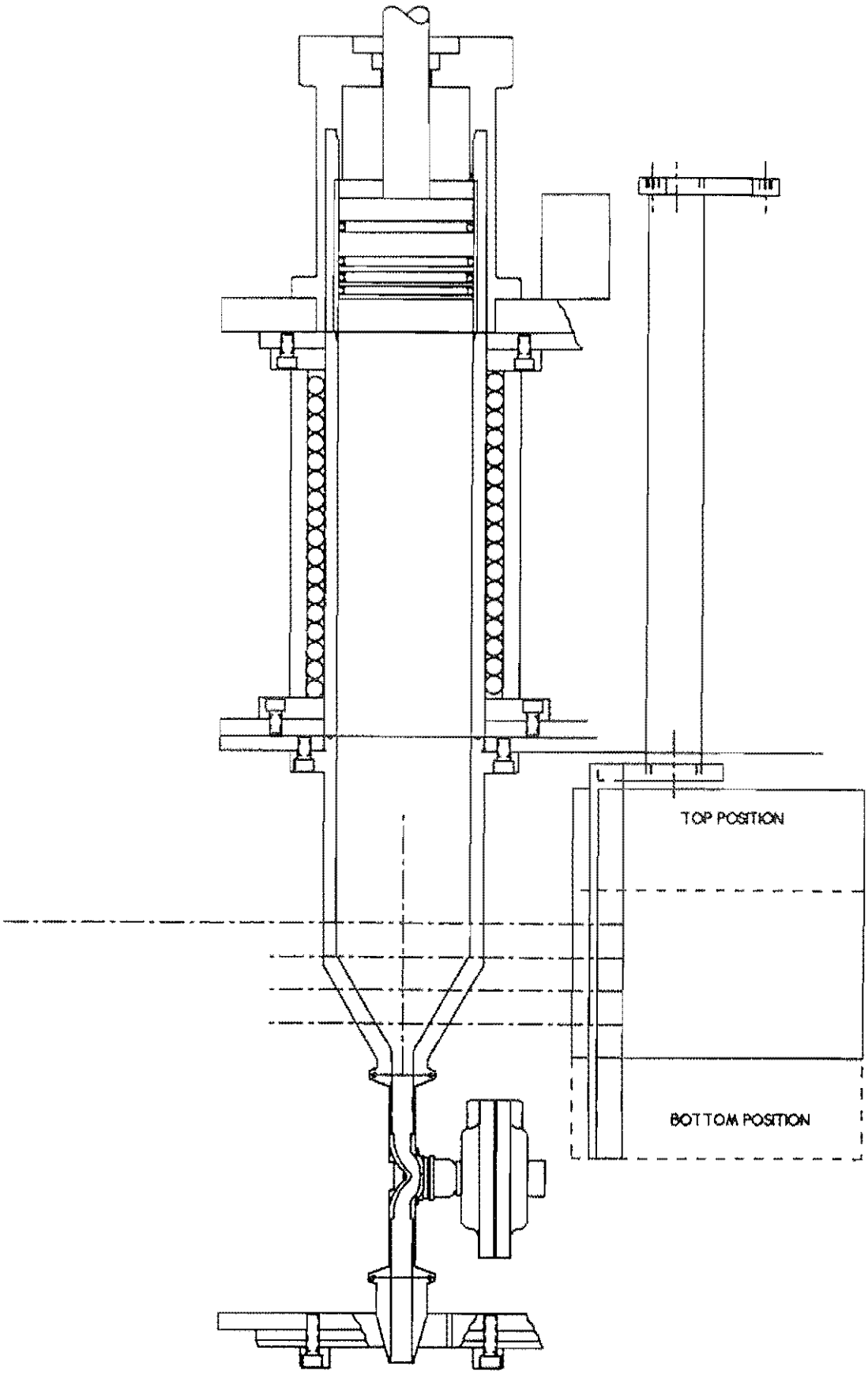
2.500
6.750
9.000
13.250
14.500


TOP POSITION
BOTTOM POSITION

Control Objectives for Neural Net Algorithm

The influence of process geometry upon the flow of PBXs can be evaluated using a 50 mCu Cesium 137 gamma ray source densitometer:

[1] To determine specific PBX momentum characteristics ($Q = f(\Delta P)$) in various geometries

[2] To determine specific PBX mass transport characteristics ($dm/dt = f(d\rho/dt, Q)$) in various geometries

CONCLUSIONS for BLU-97 submunition:

[1] Phillips model and LANL experiments indicate demixing can occur quickly, as soon as 12 pipe diameters (or 12 L/D) for $\phi =$ about 0.45 or 0.50. NMRI results from SNL also indicate demixing of PBXN-107 simulant. SNL "GOMA" code suggests that all shear is upstream of bomblet filling, and streaklines compare well with NSWC density gradient analysis.

(a) replace 1/2" plumbing and diaphram valve with 1" plumbing and diaphram valve. This changes the conical contraction from 8:1 to 4:1.

(b) install a static mixer downstream of the injection piston, in the 1" plumbing.

[2] Process engineering data suggests that compression of PBXN-107 can collapse voids:

(a) install gamma ray densitometer to quantify $\Delta\rho$ as a function of Q and P.

(b) use LANL "neural net" code to match process data for x and v versus time, and/or γ and τ versus time.

[3] Demonstrate process control for thermosetting and thermoplastic PBX materials. Perform material balances to assess pollution reduction. Transition to JSOW and Tomahawk Program Offices.

CONCLUSIONS:

HAVING DEMONSTRATED A SOLUTION FOR AN EXAMPLE PROBLEM, WE WILL DEMONSTRATE THE APPLICATION OF COMPUTATIONAL TOOLS TO THE PROCESS CONTROL OF TWIN SCREW EXTRUSION OF PROPELLANT FOR LEVERAGED PROGRAMS WHICH INCLUDE CPOCP (2.75 ROCKET), STANDARD MISSILE (MK 104 MOTOR), AND OTHERS.

SNPE
PROPULSION

" Continuous Processing of Composite Propellant " (CPOCP) a joint project between

SNPE and NSWC Naval Surface Warfare Center INDIAN HEAD DIVISION

J.M Tauzia
E.Giraud

C.Murphy

Continuous mixers and extruders User's Group Meeting
Alexandria, September 20-22, 1995

SNPE
PROPULSION

Summary

Presentation of the CPOCP Project

SNPE facilities and achievements

NSWC IHDiv facility and achievements

Conclusion

SNPE
PROPULSION

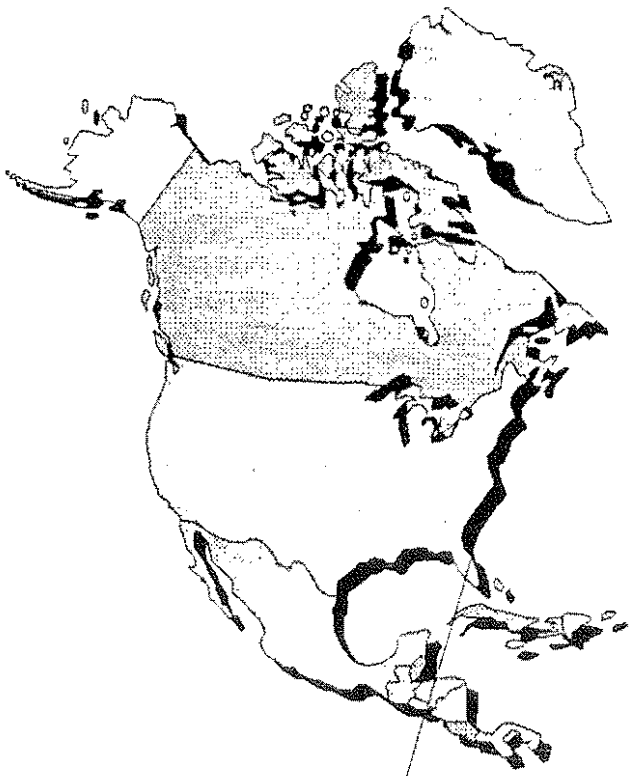
Objectives of the CPOCP Project :

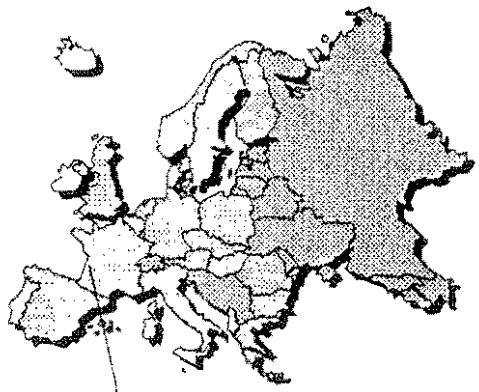
1°) Develop the technology for the production of composite propellant in a **safe** and **efficient** manner **utilizing continuous processing equipment**

2°) Arrive at a common methodology for the design of continuous processing equipment for composite propellants

SNPE
PROPULSION

Participants of the CPCOP Project :





NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

Naval Sea Systems Command

U.S.A

SNPE

France

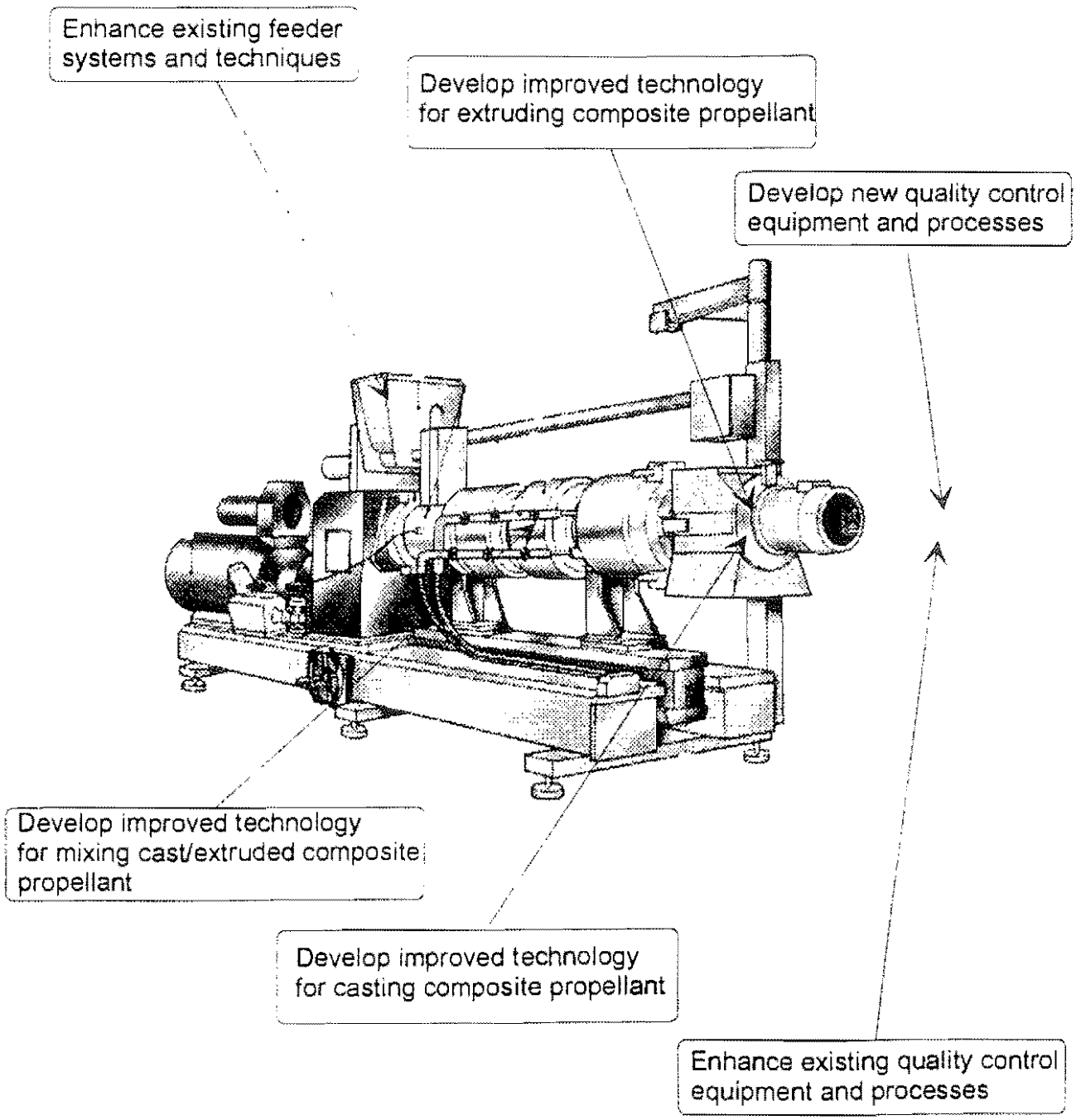
Continuous mixers and extruders User's Group Meeting
Alexandria, September 20-22, 1995

SNPE PROPULSION

Share of the major tasks as listed in the M.O.A

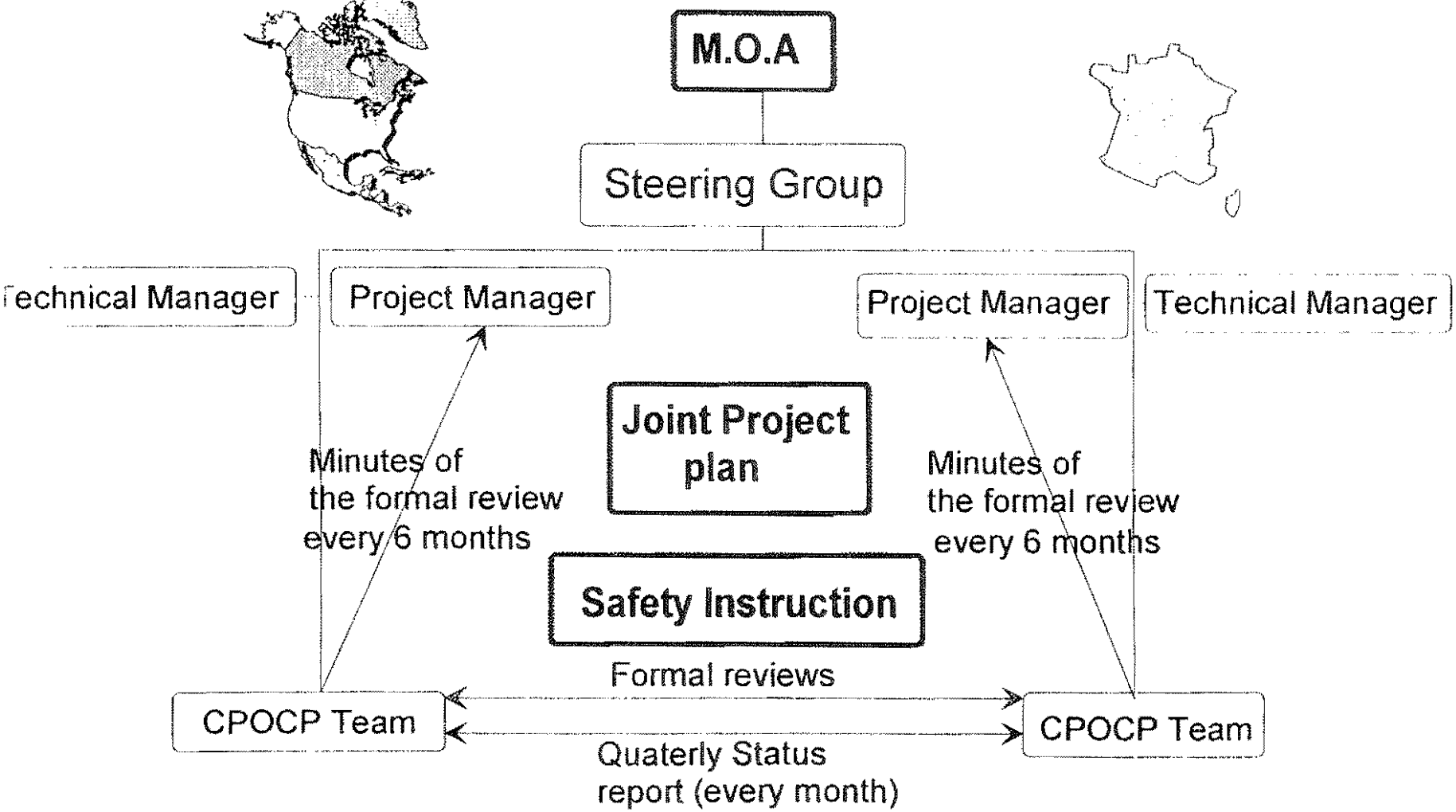
* U.S Tasks : Continuous EXTRUSION of Composite Propellant

* French Tasks : Continuous CASTING of Composite Propellant



SNPE PROPULSION

Joint Project on CPOCP Organisation



SNPE
PROPULSION

CPOCP French Organisation

Steering Group Member :
P.Lusseyran
DOD France

Project Manager :
J.Y Kermarrec
DOD France

Technical Manager :
J.M Tauzia
SNPE St-Médard

Continuous Processing Technology :
E.Giraud
SNPE St-Médard

Continuous Processing Formulation :
G.Chounet
L.Minguet
SNPE St-Médard

St-Médard plant Facility :
S.Martegoute
P.Legoff

Research Center Facility :
B.Mahé
P.Ragon

SNPE PROPULSION

Saint-Médard plant facility

Facility upgraded in January 1994

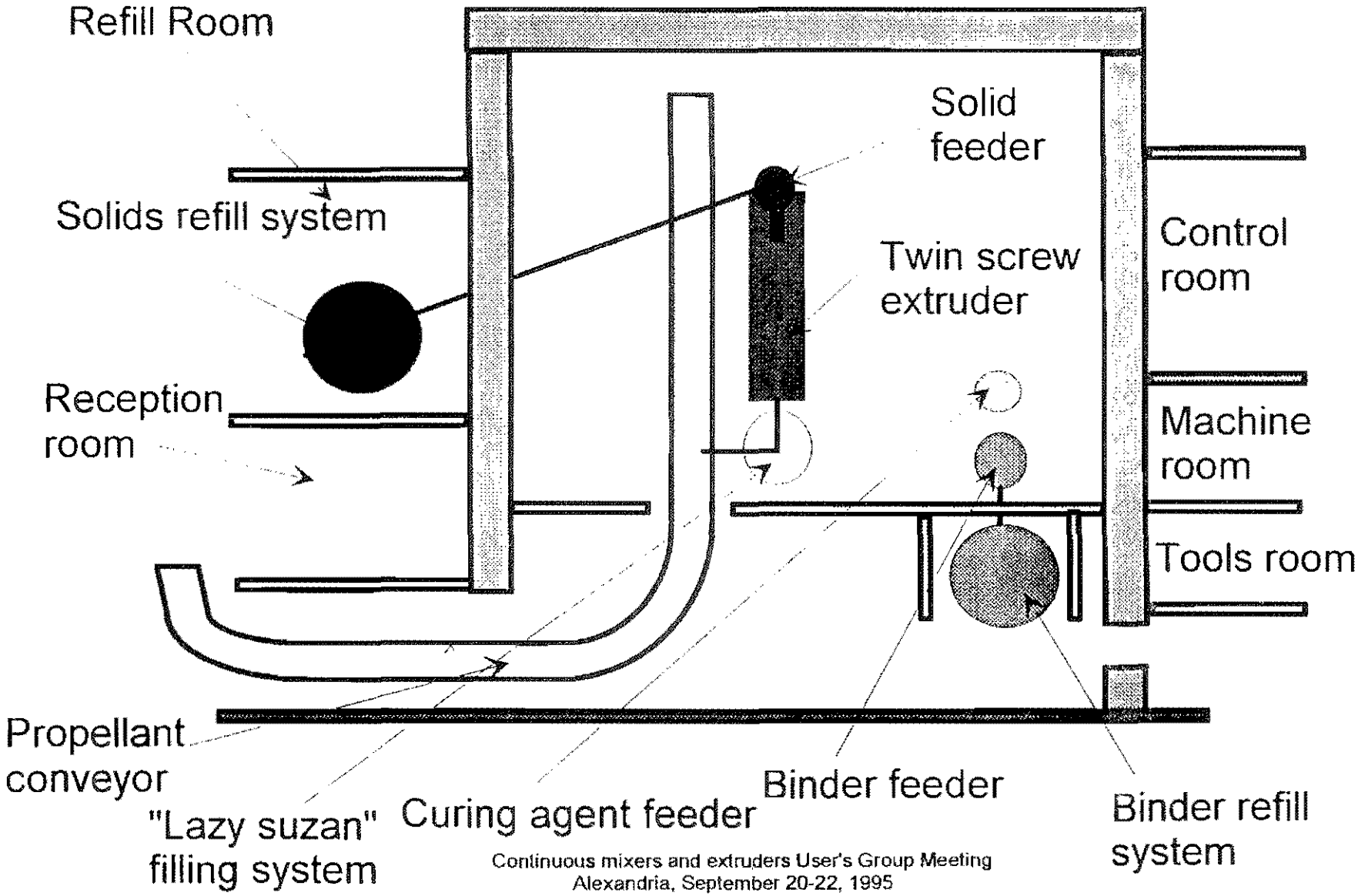
Live start up on May 10 / 94

Energetic materials handled :

* Ether/ alcohol single base
* Acetone single base
* Solvent double base
* Solventless double base
* Multi-base
* Lova propellant
* PBX
* Composite propellant

SNPE PROPULSION

Saint-Medard Plant Facility Configuration



SNPE
PROPULSION

Saint-médard plant facility

Achievements :

- 6 tons (12000 pounds) of live composite propellant manufactured.

- Live extended runs : 8 hours with Ariane V launcher propellant.

- St-Médard facility configuration ready for live M.O.A tests.

Naval Sea Systems Command

NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

U.S. Project Team

Continuous Processing Team

Connie Murphy
Rich Muscato
Bill Newton
Mitch Gallant
Mark Michienzi
Sharp Johnson

Partners

The Highly Filled Materials Institute
at Stevens Institute of Technology (HfMI/SIT)

University of Maryland at College Park (UMCP)

Applied Ordnance Technology, Inc. (AOT)

Naval Sea Systems Command

NSWC
Naval Surface Warfare Center
INDIAN HEAD DIVISION

Accomplishments

- Identified extruded composite rocket motor system
- Completed facility upgrade construction/start up
- Brought a new data acquisition system on-line
- Validated a new feeder calibration technique
- Finalized the feed stream scenario and conducted feeder testing

Accomplishments

- Identified on-line quality control technologies
- Demonstrated solventless processing of inert extruded composite propellant
- Characterized rheological properties
- Employed mathematical models for die designs

Naval Sea Systems Command

NSWC

Naval Surface Warfare Center

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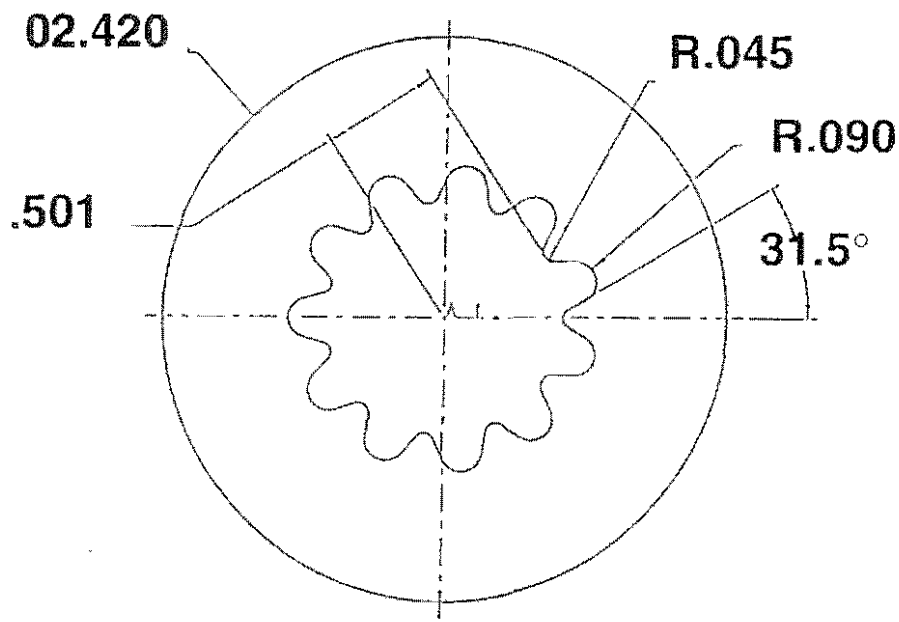
Extruded Composite Propellant Grain



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Data Acquisition System

- Previous System (FY 93-94)
  - —Data recording was too slow
  - —Data retrieval was labor intensive
  - —Very difficult to use
- New System (FY 95)
  - —Data recording optimized
  - —Data retrieval simplified and real time
  - —Easy to use
  - —Program user alarms
  - —View status of ladder logic

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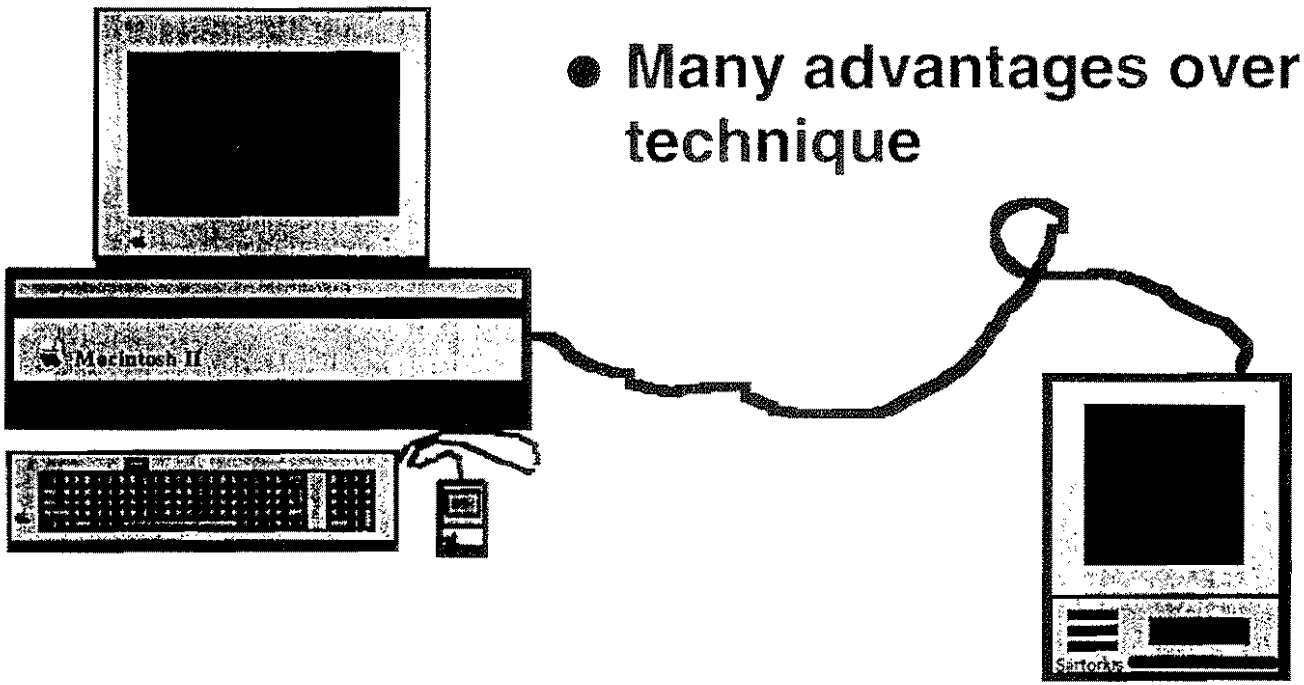
New Calibration Technique

- Automated technique for measuring and analyzing feeder performance



- Many advantages over previous technique

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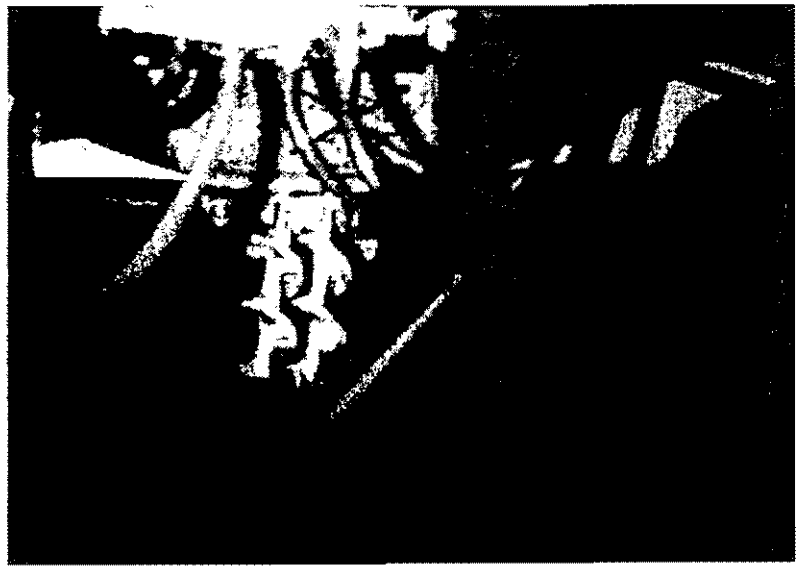
HyTemp Feeding

- HyTemp (as received) has a tendency to self-agglomerate
  - —Particles are somewhat tacky
  - —Particle elongation will seed agglomeration
  - —Long term storage greatly increases the degree of agglomeration



- Solutions Attempted
  - —Cryogenic grinding
  - —Anti-stick agents
  - —Feeder modifications

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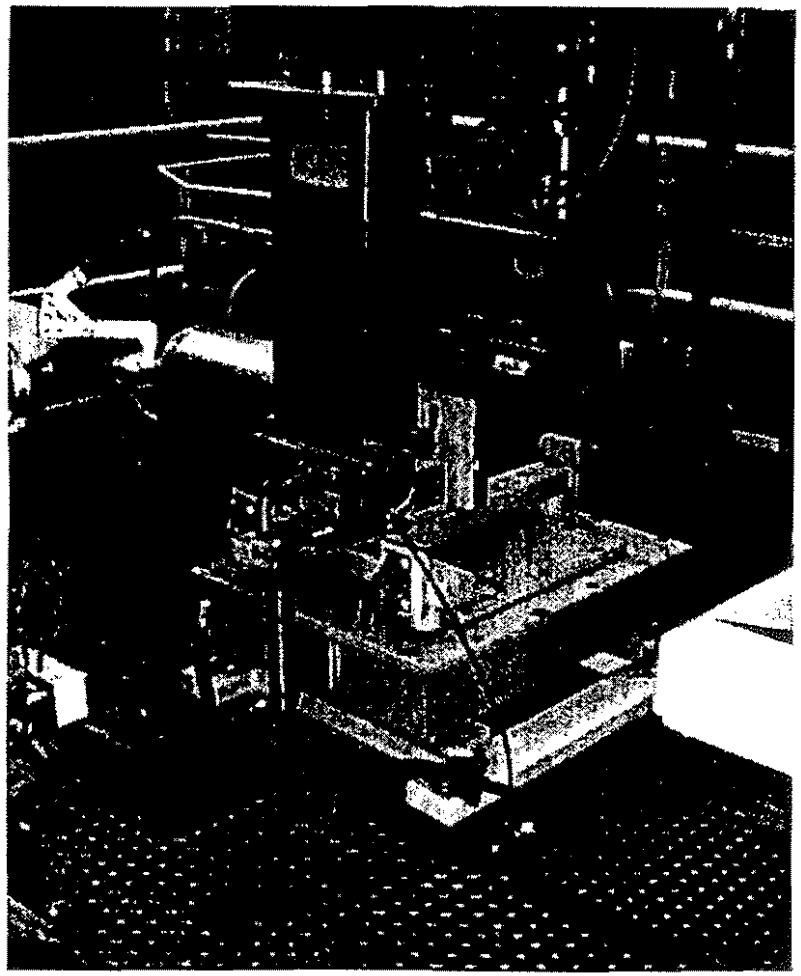
K-Tron T-20 Feeder



- Features
  - —Twin screw
  - —Horizontally agitated
  - —Maximum feed rate of 10 lb/hr
- Limitations
  - —Bridging at hopper capacities above ~ 4 lbs
  - —Can not agitate
  - —Screw threading (~25% of screw in the hopper)

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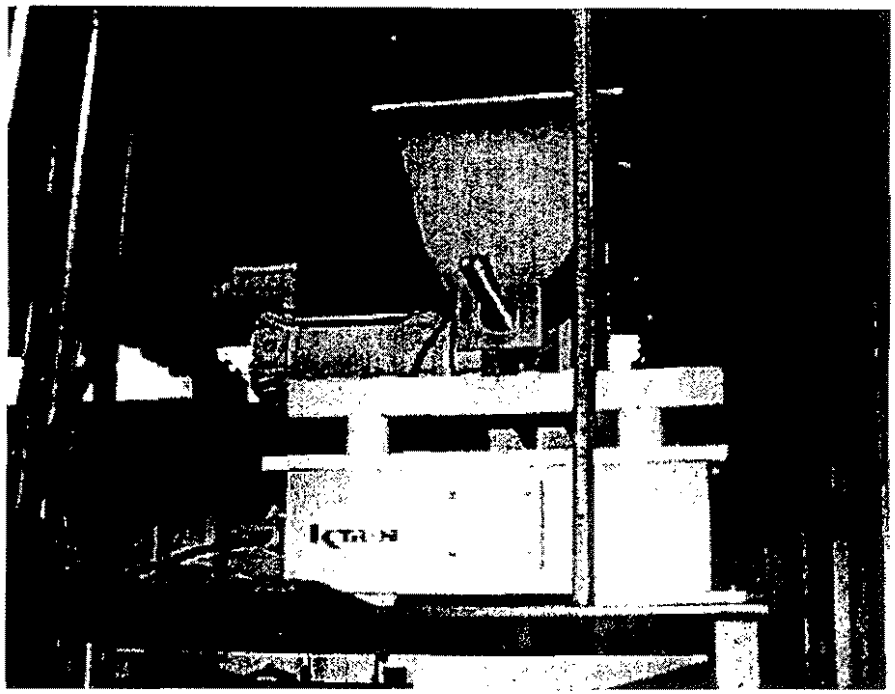
K-Tron S-200 Feeder



- **Configuration**
  - Screw (15 mm)/feed tube (27 mm)
  - Screw threading is ~90%
  - No agitator
  - No hopper extension
- **Initial test results**
  - Will function at higher hopper volumes ~ 14 lbs
  - Agitation does not seem necessary
  - Material feeds from the back of the hopper
  - Accuracy is no better than T-20

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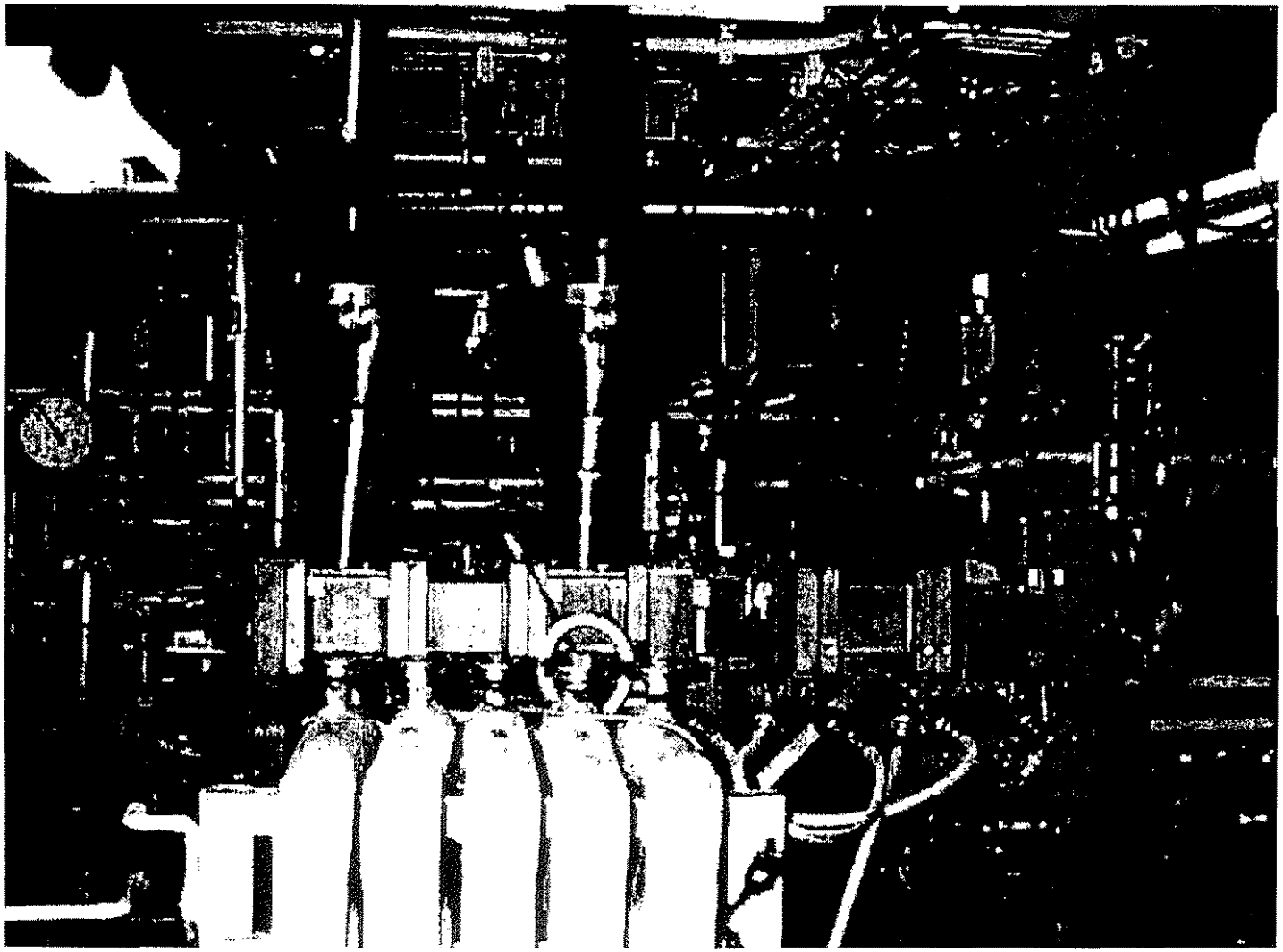
Inert Processing



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Inert Processing Results

- Successfully processed without any solvent
- Monitored pressure and temperatures along extruder
- Developed a purging technique

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Rheological Characterization Results

- Material is a viscoplastic fluid with a high yield stress: $\tau_w = \tau_0 + m_0\dot{\gamma}^n$
- Solid like behavior is shown by:
  - —the lack of extrudate swell
  - —plug like flow in channels
- Viscoplasticity gives rise to high wall slip velocities

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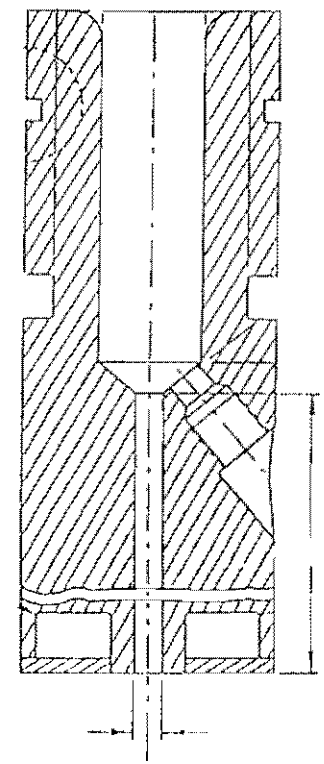
Capillary Dies

- Designed and fabricated 7 capillary dies
- Unique capability
- Inert testing completed
- Live testing scheduled for Sept-Oct 95



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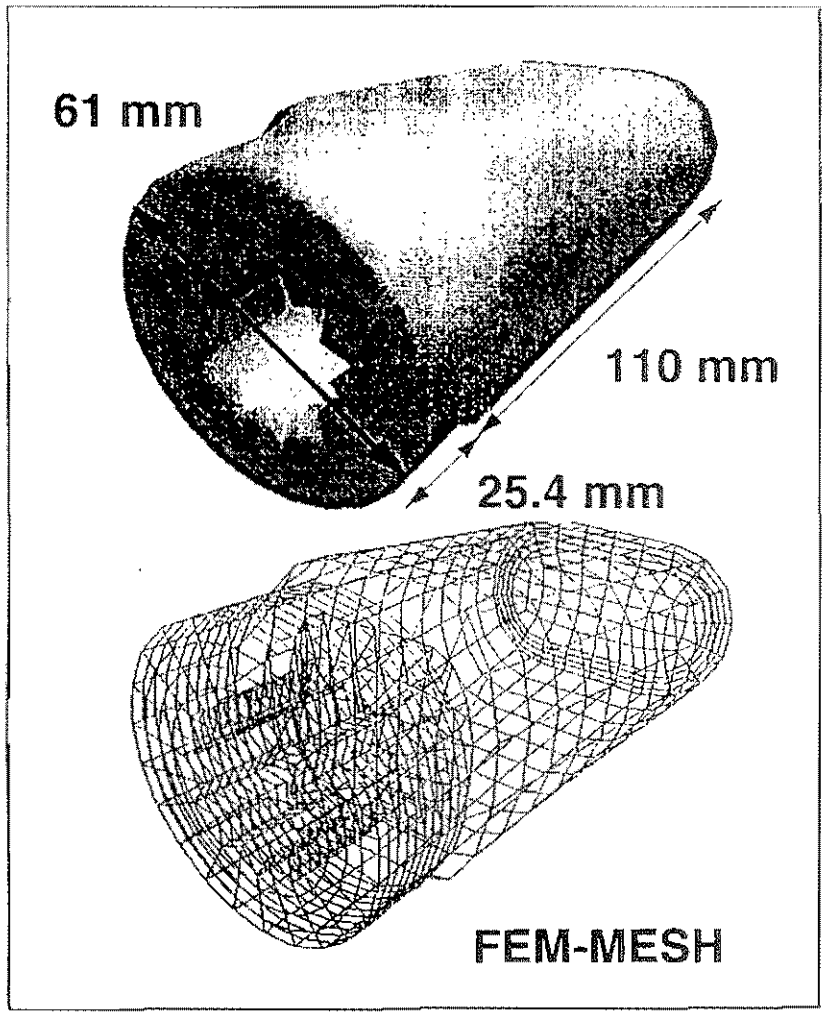
Mathematical Modeling



- Conducted weld line healing experiments
- Developed FEM meshes
  - Small scale extrusion dies
  - Full scale extrusion die

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On-Line Quality Control Approach

- Determine propellant chemistry
- Techniques to collect process data
- Determine propellant physical properties

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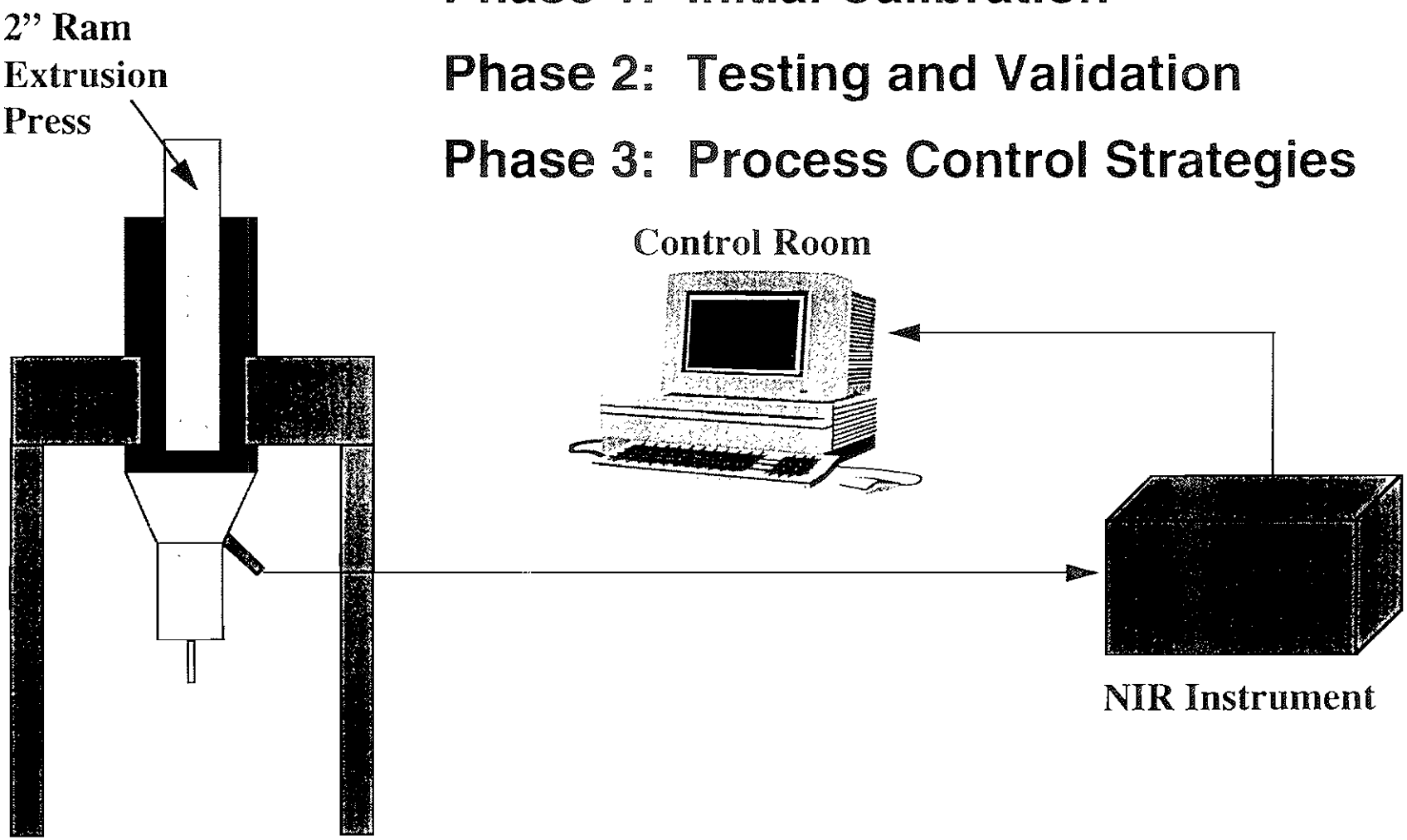
NIR Development

Phase 1: Initial Calibration

Phase 2: Testing and Validation

Phase 3: Process Control Strategies



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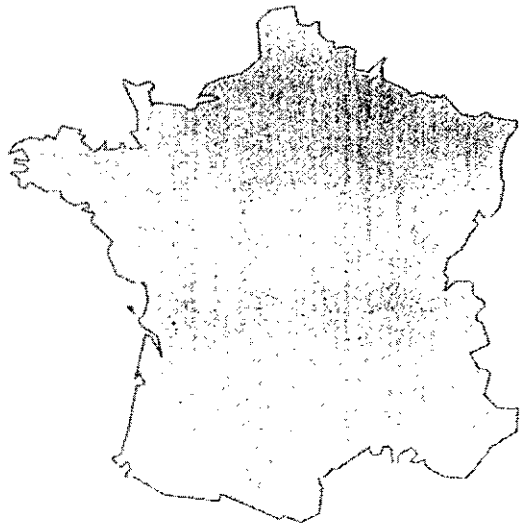
Second Year Plans

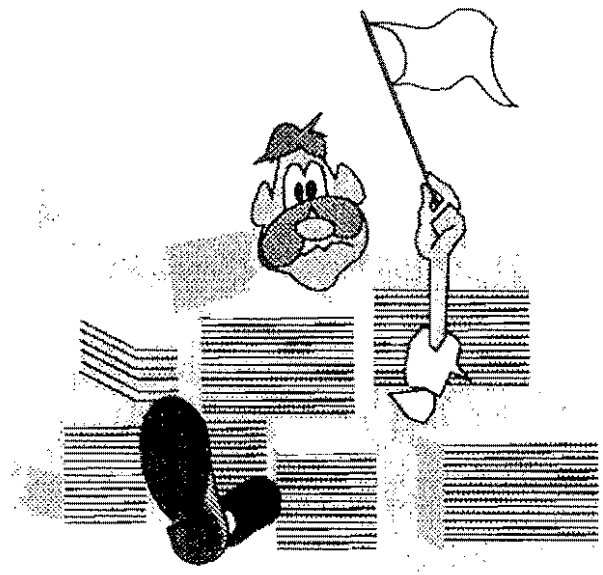


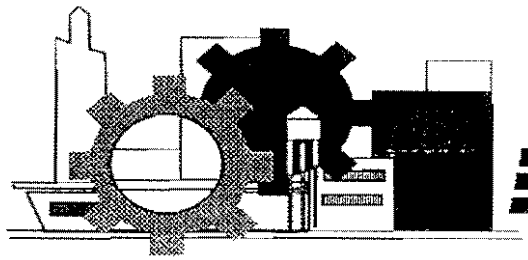
- SNPE
  - —First live testing
  - —Extended run
  - —Manufacture rocket motors

- IHDIV, NSWC
  - —First live testing
  - —First extrusion of a rocket motor
  - —QC system on-line

SNPE PROPULSION

Lessons Learned Feeders and Material Handling When Feeding a Twin Screw Processor





- Segregation of Material (Stevens Institute of Technology)
  - Different Particle Sizes
  - Different Densities
  - Elutriation
- Loss in Weight Feeders (Control and Metering)
  - Listing of customer preferences

- Material Handling (Thiokol)
  - Metal Powder Handling
  - Twin-Screw Feeder Gear Box
  - Conveyor Monitor
- Material Handling (Aerojet)
  - Handling AP
  - Equipment Requirements

Format

- Title
- Program or Product
- Keywords
- Background
- Lesson Leaned

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Feed Variance Limitations for Co-Rotating Intermeshing Twin Screw Extruders

John Curry - Manager, Process Development
Arash Kiani,Ph.D.- Senior Development Engineer *
Adam Dreiblatt- Manager, Food Technology †

February 13, 1991

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Dedicated to the memory of our colleague, Dipl. Ing. Heinz Herrmann, who through determined persistence, brought order to the art of Twin Screw Compounding.

Abstract

The extent of feeder error to survive a plasticating compounding extruder is addressed in this theoretical and experimental study. Results of unit step and cyclic variation of tracer concentration were used to define the transfer function and damping ratio respectively. The frequency dependent damping ratio of cyclically varying tracer content in the feedstream was predicted for three screw configurations with fair agreement to experiment.

Introduction

Twin screw extruders are utilized as continuous mixers, reactors, and devolatilizers for viscous fluids and slurries. An important class of twin screw devices is the co-rotating intermeshing extruder, prized for its self wiping characteristic and ability to generate high shear stresses upon small process volumes. Because these continuous mixers can be operated in a starve fed mode, ingredients are often separately metered into the process. This practice has significant operating advantages such as reduced material handling, quick transition between products, reduced in-process storage, and enhanced possibilities for process control. Where accurate constituent concentrations are required in the product, the feeder errors are constrained by the limited backmixing capability of the mixer.

To be able to specify feeder accuracy criteria based upon product constituent variance limitations, one must understand the transport characteristics of the components through the mixing system. This is done either as a modelling exercise or through reduction of experimental residence time distribution (RTD) data.

A few analytical expressions for residence time in extruders have been developed [1, 2] but their application is limited to simple geometries, fluids, and without consideration of pressure flows. Flow simulation of complex mixer geometries by numerical techniques has been reported [3] but the analysis requires significant geometry simplification. Techniques for experimentally determining RTD for extruders and interpretation of results has seen substantial treatment in the literature. Golba [4] successfully measured the RTD of a twin screw compounder on line by measuring the relative dielectic constant of the tracer in the die. Many authors have used off line colorimetric techniques and some have used low grade isotope tracers.

Among others, Herrmann [5] has reported the effect of mixer geometry upon RTD for co-rotating intermeshing extruders. Todd [6] correlated his results to the single parameter Taylor diffusion model. Altomare and Ghozzi [7] used the two parameter fractional tubularity model. Potente [8] finds even better representation with a four parameter Gauss-Weibull function. Mixer response to transients in the feed streams for extrusion systems has not been widely reported. Balke [9] showed a methodology for predicting product concentration in extruded composites. He developed explicit predictions for first order mixers [1] with high frequency normally distributed feeder error.

This paper reports analysis of an experimental study in which three screw designs were characterized for their RTD's by the unit step technique. Only one fluid, one RPM,

[1] First order mixer - A mixer whose residence time follows a first order differential equation i.e., $m\frac{dy}{dt} + ny(t) = x(t)$ where m and n are coefficients, $x(t)$ is the input (feeder) function and $y(t)$ is the output (product) function.

rate, and die pressure was analyzed. The melt mixing (MM) zone of each design was characterized in a separate experiment. The die RTD was numerically simulated. The feed system, extruder, and die are modelled as a serial network. The feed system was driven in a regular cycle at two periods for each screw and product tracer content was monitored. The experimentally observed damping is compared to theory.

Theory

The traditional method for predicting output from a composite system (e.g feeder, extruder, die) is to apply the principles of linear[2] superposition and convolution. Linearity is generally assumed for a limited range of tracer fluctuation around the operating point. Continuous mixer systems can be analyzed by convolution techniques when their transfer functions are experimentally determined. In this paper, the data is collected and reduced for the following extruder subsystems.

- The feeder output signal is taken as the system input function.
- The RTD for the solids pumping and melting section of the extruder is found by deconvolution.
- The RTD for the melt mixing and pumping section is experimentally determined.
- The die flow is numerically modelled and an RTD is calculated from the simulation.

The RTD for the die can be approximated numerically. The velocity profile was calculated using a Galerkin FEM analysis of the die momentum balance for a plug flow inlet. The RTD results from dividing a streamline lengths by a streamline velocities and a transfer function is calculated for the die. Now, the experimental melt mixing transfer function can be separated from the die by deconvolution. This system dissection makes the contribution of each extruder element to backmixing clear, and separates die effects from mixer effects.

A network representation of the exprimental system is shown in figure 1A along with the appropriate convolution expressions. A block diagram of conducted experiments is shown as figure 1B. As explained later, the experimentally determined cumulative residence time functions, F(t), are converted to transfer functions [3]. From the experiments, transfer functions for the extruder and for the melt mixing section with die can be calculated.

Finally, the product composition variance can be predicted by solving the convolution of feeder input with extruder transfer function as shown in figure 1.

[2] Linear superposition requires that each sub system is described by a linear differential equation, i.e product composition is a function of time and inlet condition but not a function of itself nor deverivatives of itself.

[3] Transfer function - ratio of the Laplace transforms of the product concentration function to the feed concentration function. The product concentration is the inverse transform of the product of feed concentration transform and transfer function.

Experimental and Data Analysis

The experimental arrangement is described in figure 2. Two compounding extruders are coupled in a crosshead fashion. The sidestream extruder is configured identically to the main extruder's feed and melting section. The sidestream extruder is coupled at a three-way valve. Base resin and tracer compound are fed from separate gravimetric feeders. The die is fitted with an AC excited parallel plate capacitance cell. RTD characterization is based upon sensing tracer content in the flowing product at the die. The feed tracer content is resolved from the mass flow signals of the feeders. The product tracer content is related to the strong dielectric response of tracer compared to base resin.

The base resin is a low density polyethylene (BP33 Lot SZ772) with an MI of 2. The tracer is a precompounded pellet of 5% (vol) conductive carbon (Cabot XC72) in the same base resin. The shear viscosity difference between base resin and tracer is less than 5% over the $10 - 1000\ \mathrm{sec}^{-1}$ shear rate range at 240°C.

The base resin feeder is a K-Tron GF06 gravimetric belt feeder and the tracer feeder is a K-Tron T-20 loss in weight screw feeder.

The plasticating mixers are both Werner & Pfleiderer ZSK-30 co-rotating intermeshing extruders. To execute a unit step of tracer concentration to the test extruder, the resin feeder was stopped and tracer feeder was started. To execute a unit step of tracer concentration to the melt mixing and die of the test extruder, a more complicated procedure is required.

Both extruders were run at identical rate with the side stream extruder melting tracer and dumping to the floor via the 3-way valve. To effect a unit step, the base resin feeder was stopped and the 3-way valve was tripped by a low level pressure alarm of the pressure trigger. This action puts the diverted tracer melt stream on line. To execute a cyclic variation of tracer content in the feed stream, the tracer feeder setpoint was driven by a sine function signal generator.

The geometry of the melt mixing section of the test extruder was configured as screws 1, 2, and 3 by choice and sequence of the modular elements. Screw 1 contains screw elements, screw 2 contains kneading discs of both right and left handed helix and screw 3 contains kneading discs with neutral stagger between successive disc. RPM (250) and throughput (22.5 pph mean) were fixed so that pressure and melt temperature were steady 1000 psi and 250°C respectively. For the cyclic feed experiments, the tracer feeder was run steadily at 3.5 pph and cycled between 6.1 pph and 0.9 pph. This paper then concerns the effects of screw configuration upon back- mixing. The die was provided by General Electric and is described by [4].

The cumulative exit age distribution and screw designs for screws 1, 2 and 3 are shown as figures 3, 4, 5. The cumulant function, $F(t)$, was calculated as:

$$F(t) = \frac{C(t)_{sample} - C(0)_{base}}{C_{tracer} - C(0)_{base}} \tag{1}$$

where C is the concentration of tracer detected by the dielectric measurement. In order to compare distributions on their relative backmixing characteristic, the cumulative

distributions were replotted against normalized time, where:

$$\theta = \frac{t}{\bar{t}} \tag{2}$$

and

$$\bar{t} = \int_0^\infty [1 - F(t)]dt \tag{3}$$

Comparative plots of the composite data and the melt section data are shown as figure 6a and 6b. The data is fit to a 3 parameter Weibull function after Potente [8].

$$F(\theta) = 1 - exp(-C_1[(\frac{\theta - P}{1 - P})^{C_2}]) \tag{4}$$

P represents the normalized transport dead time, C_1 is related to the initial cumulant rate and C_2 is related to the curvature of the RTD tail. The Weibull is a higher order fractional tubularity model. When $C_2 = 1$, the Weibull function is a solution for a first order system.

A table of coefficients which fit the Weibull function to the experimental data are presented in figure 7a and a function is plotted for the melt mixing section of screw 2 with die as figure 7b.

The calculated velocity distribution for the die and derived RTD for a plug flow input is shown as figures 8a and 8b. The die residence time function shows significant dead time and moderate backmixing behavior (slope).

System Synthesis

Admittedly plasticating extruders are not linear systems. In addition to the variables of time and the feed tracer concentration function, the local tracer concentration is also sensitive to subtle changes in degree of fill which amplify the non linear flow properties of the melt and contribute to channelling and stagnation. Differential rates of melting between tracer and base, and local pressure fields also add to nonlinear behavior. Fig 7a shows that a reasonable representation of the cumulative residence time data can be made as a linear first order system. A network for the extruder system (Fig 1) was synthesized under the following assumptions:

- Superposition of the system element responses
- Linear response over a modest range of feeder input (i.e. feeder cycle)

The transfer function H(s), is a density RTD function which is related to a cumulative age function the unit step input transform.

$$F(s) = \frac{1}{s}H(s) \tag{5}$$

The solid transport and melting transfer function can easily be deconvoluted from the experimental models (fig 1) as follows:

$$H_S(s) = \frac{C_p(s)}{H_{MM}(s)H_D(s)} \tag{6}$$

The melt mixing transfer function H_{MM} is approximated by deconvoluting the calculated die model and the melt mixing experimental model. This analysis is contrived since as an assumed unit step, input was applied to the die instead of the distribution which naturally results from the extruder. However, Fig 6b indicates a plug flow-like tendency for extruders with dies and the plug flow assumption for the screw itself should be reasonable. The deconvolution is as follows:

$$H_{MM}(s) = \frac{H_{MM}(s)H_D(s)}{H_D(s)} \tag{7}$$

The cumulative exit age distribution functions for the extruder components: solids transport and melting, melt mixing and pressurization, and die flow are shown in table 9a and figure 9b (for screw 4).

The extrusion system was also fed a regularly cycling feed signal. The feed signal was convoluted with the experimental extruder model to predict a product concentration as follows:

$$C_P(t) = U_F(t) * H_E(t) \tag{8}$$

For linear first order systems fed by a sine feed concentration function, the ratio of the amplitude of product tracer content (around a mean) to the amplitude of the fed tracer content is:

$$AR = \frac{1}{(1+\omega^2\tau^2)^{\frac{1}{2}}} \tag{9}$$

where ω is the frequecy of tracer variation. The time constant, τ , for the normalized cumulative exit age distribution is,

$$\tau = \frac{(1-P)\bar{t}}{C_1} \tag{10}$$

The predicted and experimental amplitude and transport deadtime are tabulated in figure 10.

Results

The cumulant distributions of Fig 6 reveal interesting characteristics of kneading disc mixers.

- The cumulative distributions for the test screws are easily differentiable in the tail but not otherwise. Werner [10] showed that disc width of a mixing element has effects upon both initial cumulant rate and curvature during melt mixing. The similarities in initial cumulant rate are especially strong for the melt mixing experiments.
- The neutral kneading configuration (Screw 4) of Fig 6b has the narrowest cumulant distribution. Intuitively, this is surprising since the "mixing" perform ance of a configuration improves with increasing kneading disc width and stagger angle. The distribution is narrow because the kneading disc can cause only a radial component of motion because a neutral stagger causes no cascading action from disc to successive disc. This type of mixer is pressure driven. Therefore, radial diffusion of tracer

is enhanced and the mixing section wipes out radial tracer gradient. This type of configuration has been shown [6] to fit a diffusion model with only long itudinal tracer gradient. The relatively high radial tracer gradients of the other test screws contribute to their diffuse residence time distribution as the tracer spreads in the die. Of course, the average residence time of a neutral mixing section is comparatively long.

- The dynamics of melt mixing in the test geometry are responsible for experimental discontinuities in the RTD tail distribution and the discontinuities are not represented by the model. Admittedly, the cumulant can never decrease as it sometimes does in Figs 4 and 5. This is an experimental artifact due to stagnancy in the system, a local condition which allows only radial circulation while other fluid particles are passing to the exit. The condition of stagnancy is expected according to Noar and Shinnar [11].

$$\Omega = \frac{\frac{\partial F}{\partial t}}{W} \tag{11}$$

for any situation where the intensity function is negative as in the case of a negative cumulant rate.

The action caused by disc kneaders on the melt phase depends upon melt fluidity, operating conditions and disc geometry. Low viscosity fluids are more susceptable to pressure driven flow. Processes with low viscosity fluids exhibit more backmixing than those with high viscous fluids. Degree of fill is affected by the throughput/RPM ratio. At low degree of fill, the fluid volume will have a free surface and can back flow without fluid counterpressure.

For a given ZSK compounder, the centerline and cross- sectional geometry are fixed and disc width and stagger angle between successive discs describes kneading block geometry. Typical flow fields for disc geometries of different stagger angles are shown as Fig 11a. Werner [10] modelled the mixing problem in a stack of mixing discs as a parallel network of ideal mixers. The network representation is shown as Fig 11b. The resulting RTD depends upon reflux ratio as shown in Fig 11c. In contrast to the reflux model of Werner, the melt mixing data of Fig 6b show a longer process dead time and scattering of the tail distribution. This scattering is reminiscent of the cleanout characteristic of the blocks observed in screw pulling experiments. Screw 1, the design containing screw elements, has a very regular tail distribution due to the continuous helix of this design. Screw 2, the variably staggered disc design, has a very irregular distribution due to filtering effect of restrictively staggered discs. Screw 3, the neutral staggered disc design, has a damped regularly oscillating tail distribution due to the regular discontinuities of the disc design. The tail distribution has a large influence upon the choice of curvature parameter, C_2, of the Weibull distribution.

The discretized extruder data of Fig 9 show that the backmixing is a much stronger function of solids transport and melting than melt mixing under pressure in a plasticating extruder. The solids transport and melting cumulant function for all three screws should nominally be the same since only changes to the melt mixing section differentiate the screws. The discrepancies in Fig 9a result from experimental error and from the relative non repeatability of solids transport and melting compared to fully molten flow. In any case, the solids transport and melting mechanisms of any screw tested has a more diffuse

RTD than the corresponding melt mixing section. Product compositions are therefore heavily influenced by feeder variances and solids transport and melting mechanisms.

The transient system data of Fig 10 show that long cycle feeder errors are persistent in the product and that the feeder error damping is affected by the screw configuration. The improved experimental damping performance as compared to the model prediction at long feed cycle interval for the kneading block configurations, is due to the diffuse RTD tail characteristic of these configurations in real time. As discussed, these tail distributions are not represented by a first order model. However, at the faster feed cycle frequency, even the kneading block damping performance is accurately predicted as shown in Fig 10 and Ref 9.

Feeder errors can be random or ~~systematic~~. Random errors are high frequency and normally distributed and will be effectively damped by extruders. Systematic errors result from feeder cycling about a set point, usually, as a consequence of poor controller tuning or poor material feed behavior. These errors have typical periods as shown in this experiment. The amplitude damping of the feeder by the compounding extruder can only be 50% of the long cycle feeder swings with modest deviation amplitude. Wildly cycling feed composition is probably not damped at all.

Summary

Linear system analysis was applied to a plasticating compounding extruder in order to analyze the system component contributions to mixing in time, and to predict a feeder variance effect upon product composition. The effect of screw geometry at one process operating condition and for a pellet fed LDPE with LDPE based tracers was studied. The linear system assumption was possible because for this experiement, the RTD was a high curvature function and could be approximated by a first order model. The solids transport and melt ~~mixing~~ section of the extruder is responsible for the bulk of backmixing. Except for the behavior of the residence time tail distribution and, of course, the average residence time of each screw, the normalized RTD's of the melt mixing sections of three mixing geometries are practically indistinguishable. Analysis of the residual tracer concentration in the product shows that high frequency feeder disturbances are more easily damped by the compounder and that kneading blocks are useful in damping feeder cycles.

Acknowledgements

The authors thank Dr. Joseph Golba and Mr. Richard LeBlanc of General Electric for supplying and installing their capacitance cell die, which made the experiments possible. Thanks also to Mr. Arend van der Veen of Stevens Institute for advice and calculations regarding convolution integrals.

Glossary

- F - cumulative residence time function
- H - residence time density function $= \frac{\partial F}{\partial t}$
- t - time (sec)
- $\bar{t}$ - average residence time $= \int_0^\infty [1 - F(t)]dt$
- θ - normalized time $\frac{t}{\bar{t}}$
- s - Laplace transform parameter
- $H(s)$ = Laplace Transform of H(t) $= \int_0^\infty H(t)e^{-ts}dt$
- $L^{-1}H(s)$ - (Inverse transform) = H(t)
- $H(t)_{out}$ - Convoloution Integral $= \int_0^\infty H_1(t-t')H_2(t')dt' = H_1 * H_2$
- $W(t)$ - washout function = 1 - F(t)
- $\Omega(t)$ - Residence time intensity function
- ω- frequency (cycles/sec)
- σ - reflux ratio Q_r/Q
- Q - local volumetric throughput (cc/sec)
- Q_r - local volumetric reverse flow (cc/sec)
- AR - amplitude ratio e.g $\frac{Product\ concentration\ amplitude}{Feed\ concentration\ amplitude}$

Subscripts

- P - product
- S - solids transport and melting section of extruder
- MM - melt mixing and pressurization section of extruder
- D - die
- E - composite extruder with die
- All other terms are defined in the text

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Figures

Fig 1 - Analysis Structure for Residence Time Experiments,
a) Network representation of test equipment
b) Representation of conducted experiments

Fig 2 - Flow Diagram - Residence Time Experiment

Fig 3 - Experimental Cumulative Exit Age Distribution of Total Screw with Die - Screw 1

Fig 4 - Experimental Cumulative Exit Age Distribution of Total Screw with Die - Screw 2

Fig 5 - Experimental Cumulative Exit Age Distribution of Total Screw with Die - Screw 3

Fig 6 - Experimental Cumulant Data for
a) Composite Screws 1, 2, 3 with Die
b) Melt Section Screws 1, 2, 3 with Die

Fig 7 - a) Coefficients for best Weibull Function Fit to Data
b) Weibull Function fit of Screw 2 Melt Section Incl Die

Fig 8 - a) Die Analysis (From FEM analysis of Capacitance Die)
b) Model fit of the Calculated Residence Time Distribution for the Die

Fig 9 - a) Model Coefficients for Cumulative Exit Age Distributions for Extruder parts
b) Deconvolution of Cumulative Residence Time Function for Screw 3

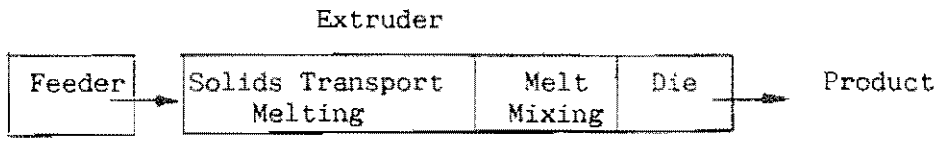
Fig 10 - Calculated and Experimental Damping of a Cyclic Feed Composition

Fig 11 - Flow in Kneading Blocks

Fig 1

ANALYSIS STRUCTURE FOR RESIDENCE TIME EXPERIMENTS

a) Network representation of test equipment



Convolution Integrals

The time dependent product composition Cp(t) depends upon input from the feeders, U(t), mixing during solids conveying and melting, $H_S(t)$, mixing of the melt, $H_{mm}(t)$ and mixing in the die, $H_D(t)$.

In the time domain

$$C_p(t) = U_F(t) * H_S(t) * H_{MM}(t) * H_D(t) = U_F(t) * H_E(t)$$

or in the LaPlace Domain

$$C_p(s) = U_F(s)\ H_S(s)\ H_{MM}(s)\ H_D(s) = U_F(s)\ H_E(s)$$

Deconvolution is performed by the inverse Laplace operator $L^{-1}\ \{C_p(s)\} = C_p(t)$

$H_E(s)$ is a transfer function for the composite extruder.

b) Representation of conducted experiments

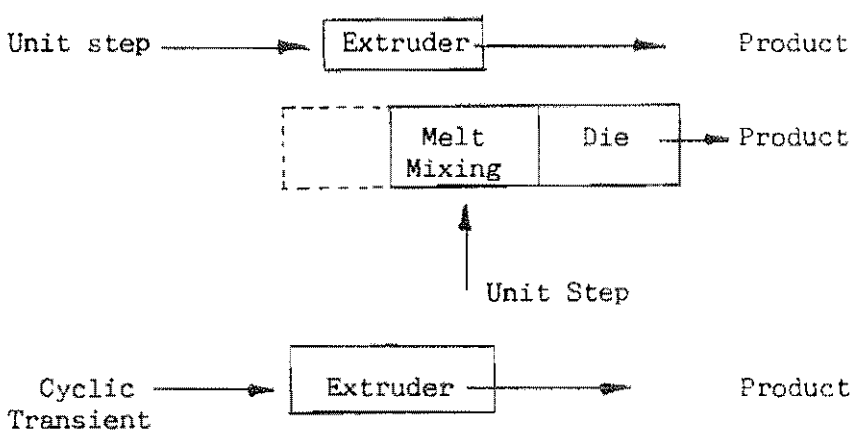


Fig 2

FLOW DIAGRAM: RESIDENCE TIME EXPERIMENT

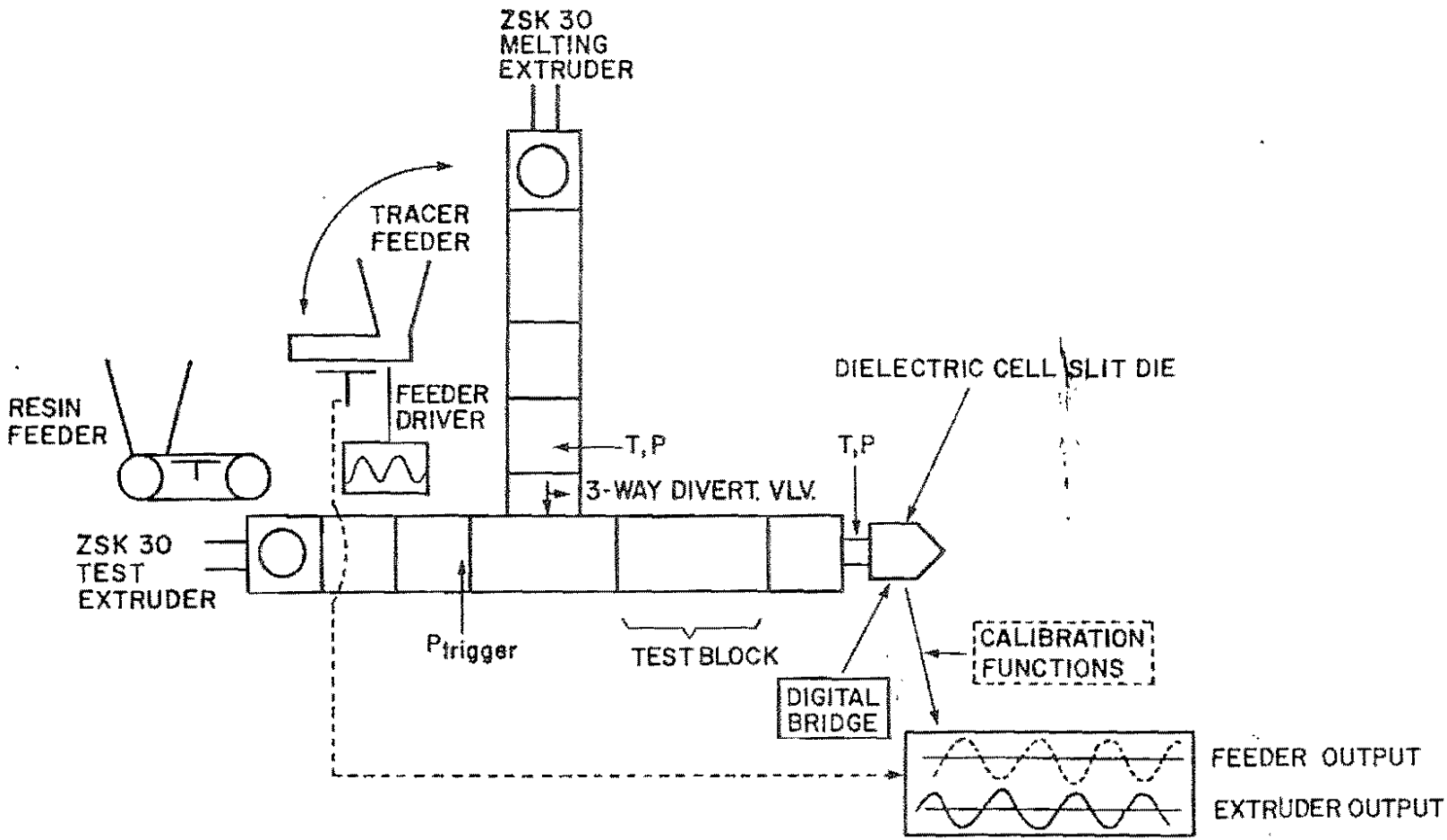
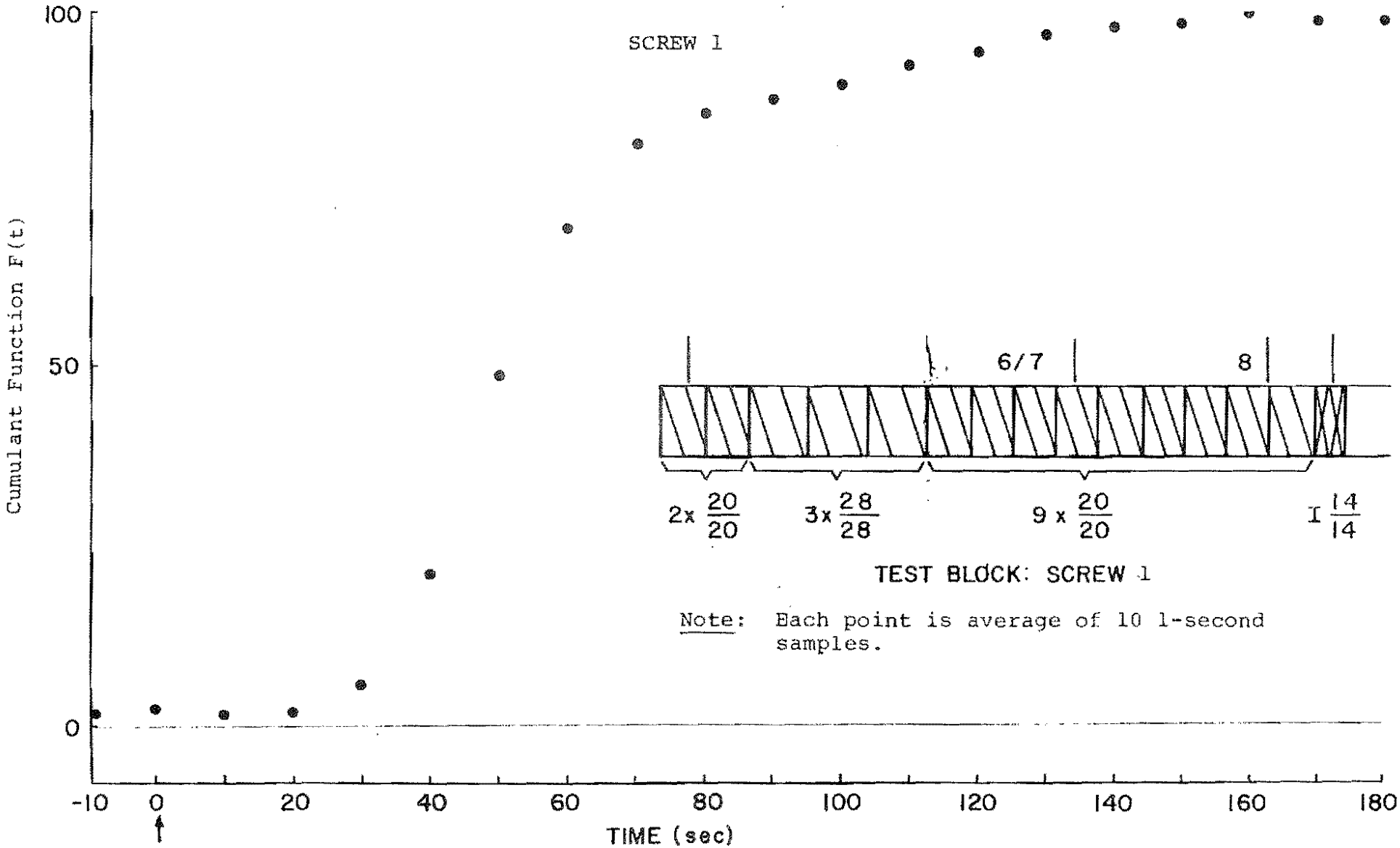


Fig 3

EXPERIMENTAL

CUMULATIVE EXIT AGE DISTRIBUTION

OF TOTAL SCREW WITH DIE



Note: Each point is average of 10 1-second samples.

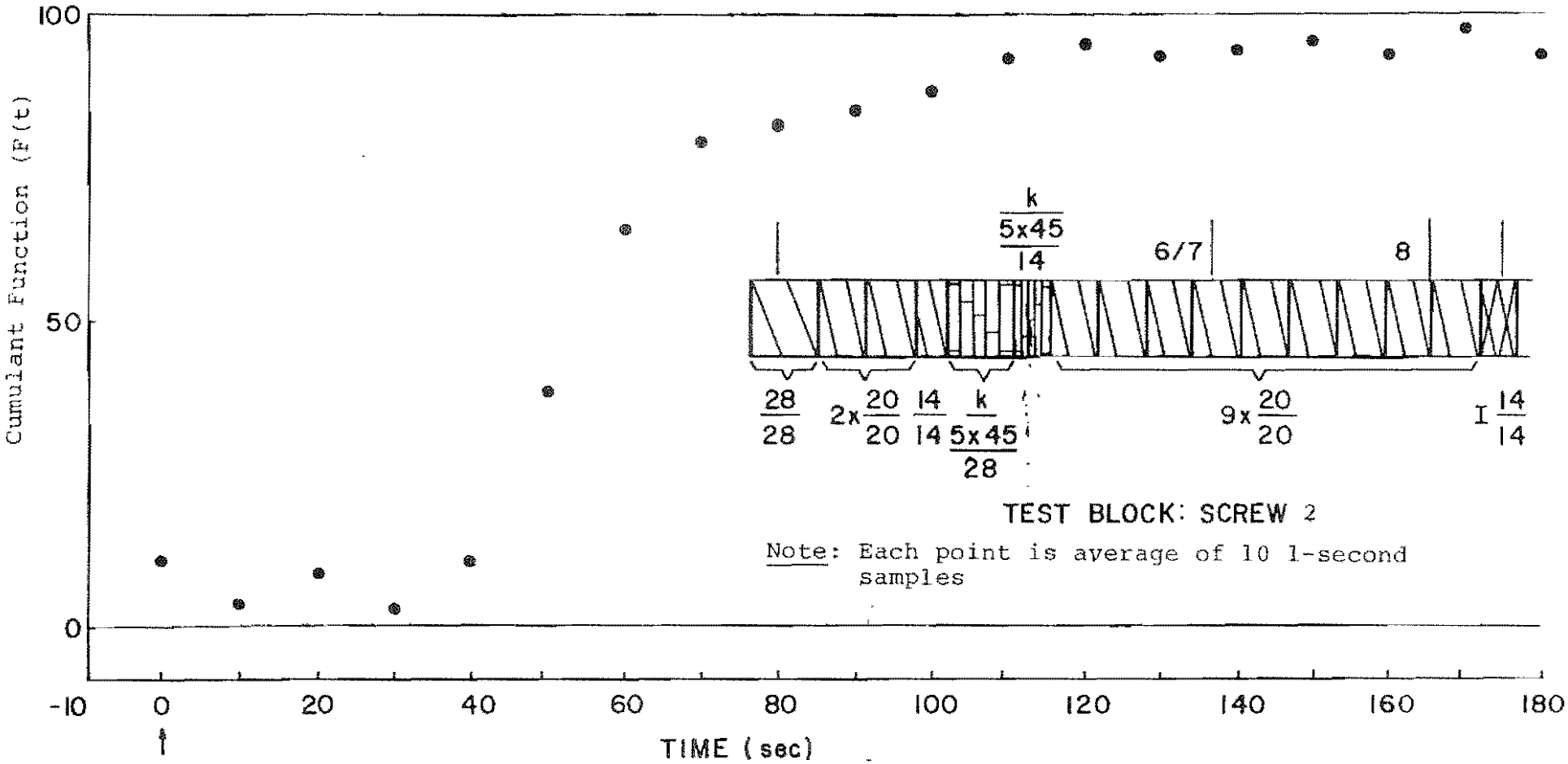
Fig 4

EXPERIMENTAL

CUMULATIVE EXIT AGE DISTRIBUTION

OF TOTAL SCREW WITH DIE

SCREW 2



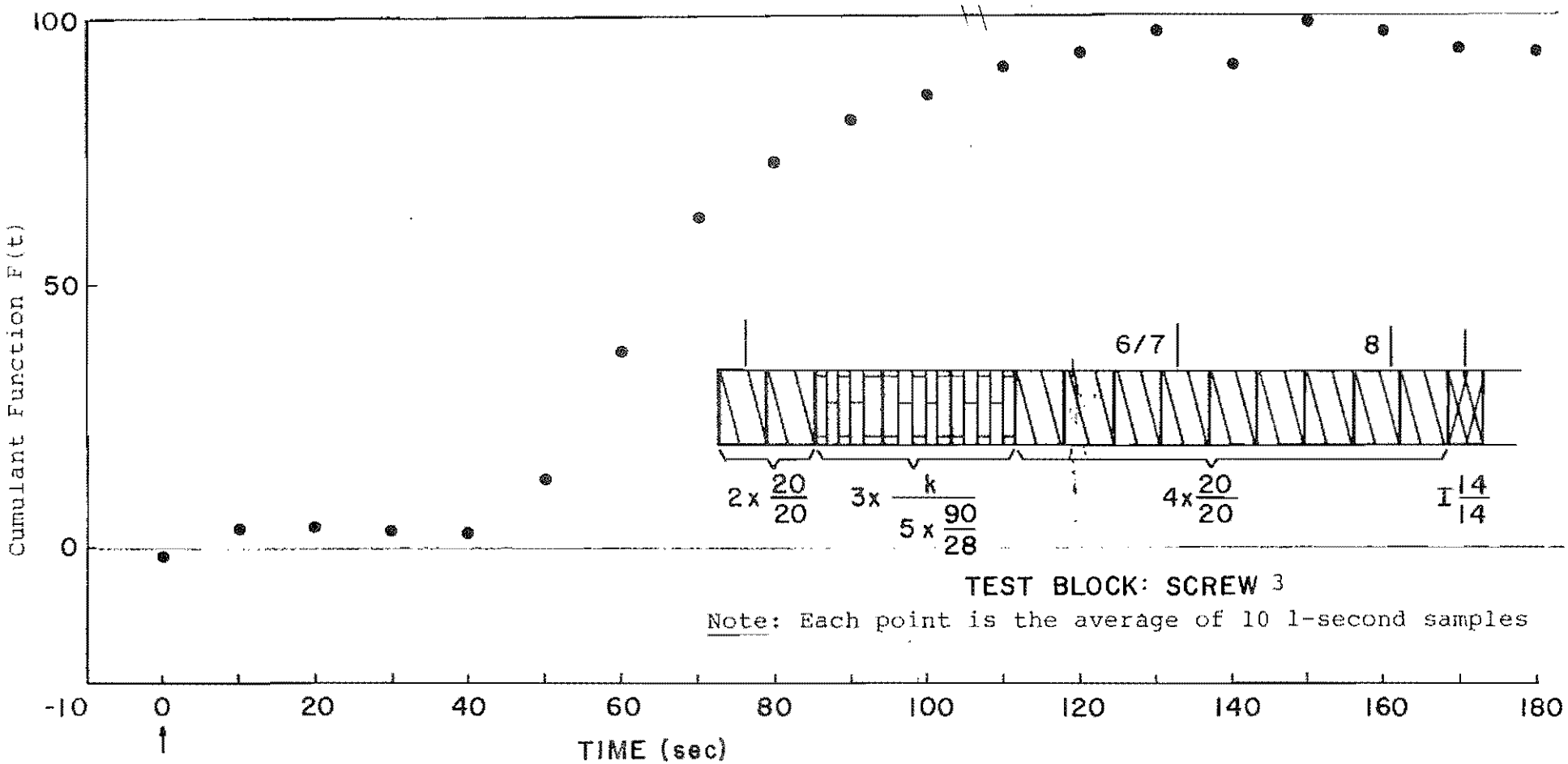
EXPERIMENTAL

Fig 5

CUMULATIVE EXIT AGE DISTRIBUTION

OF TOTAL SCREW WITH DIE

SCREW 3



Note: Each point is the average of 10 1-second samples

Fig 6a

EXPERIMENTAL CUMULANT DATA FOR
COMPOSITE SCREWS
1,2,3 WITH DIE

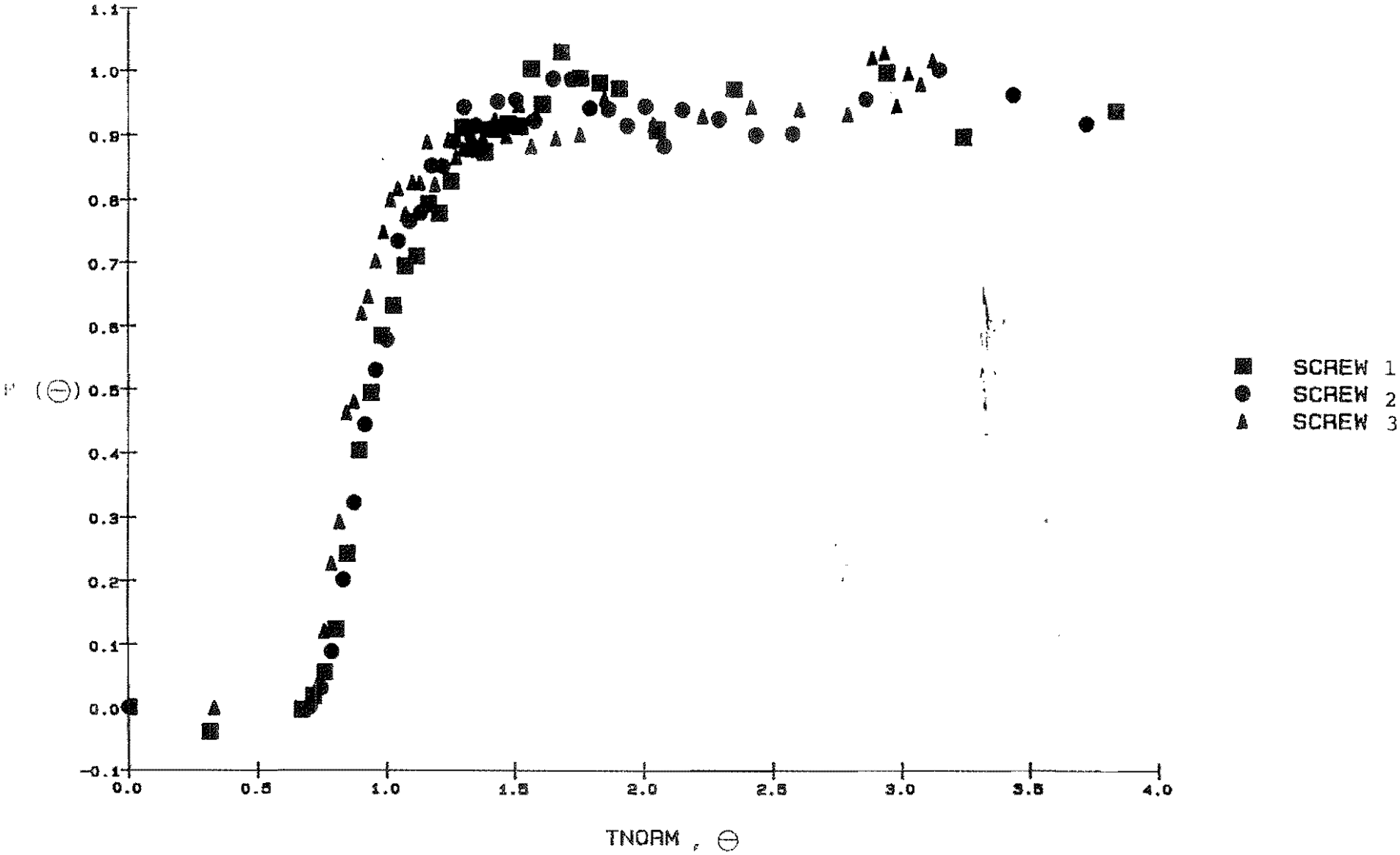


Fig 6b

EXPERIMENTAL CUMULANT DATA FOR
MELT SECTION SCREWS 1,2,3 WITH DIE

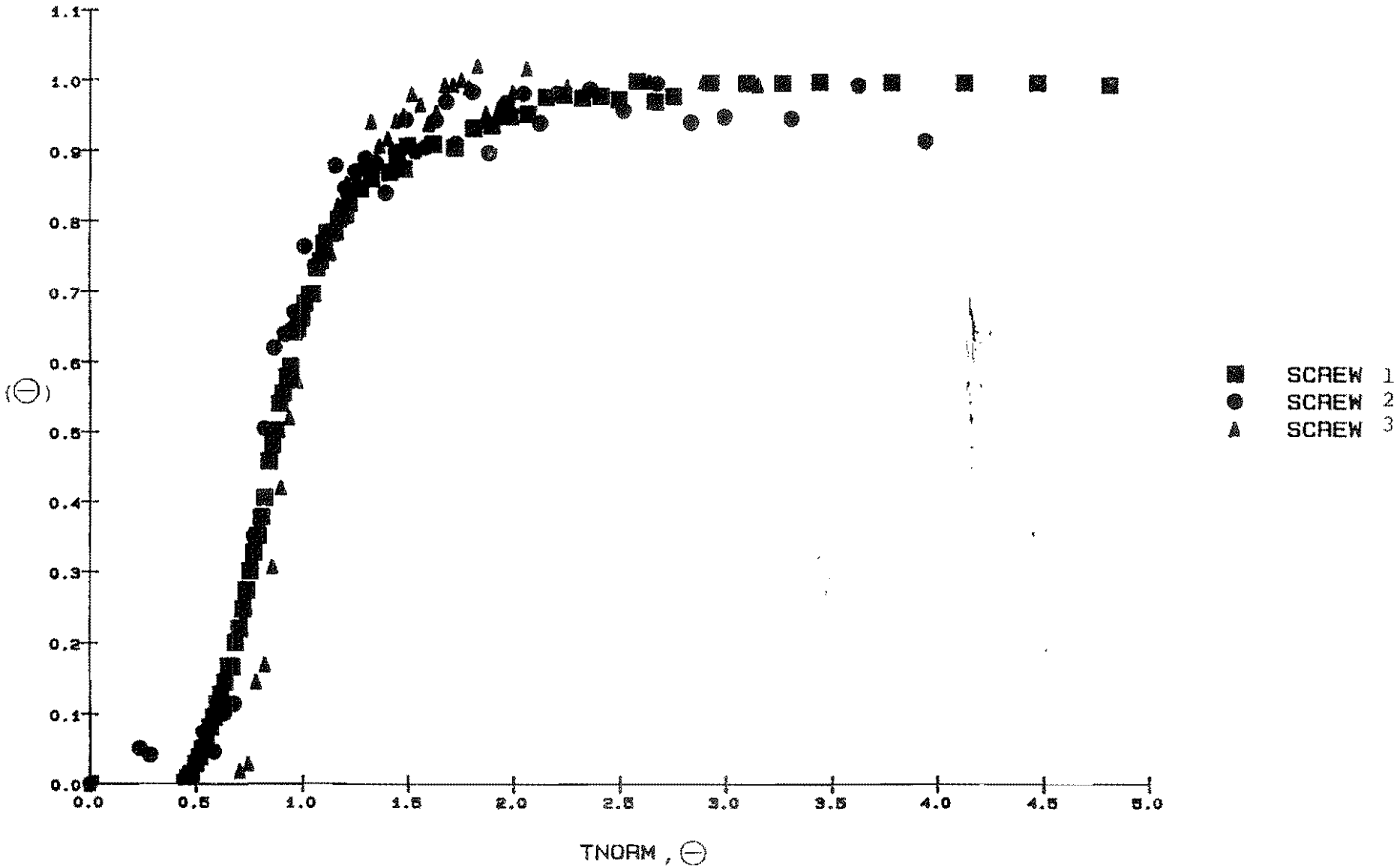


Fig 7a

Coefficients for best Weibull Function Fit to Data

$$F = 1\text{-Exp}\left(-C_1\left((\Theta - P)/(1-P)\right) ** C_2\right)$$

Screw	C_1	P	C_2*	$\bar{t}$, $\Theta = t/\bar{t}$
1 melt	1.1 (.9)	0.45	1 (1.3)	58
1 composite	0.9	0.7	1	67.45
2 melt	1.1	0.5	1	63.29
2 composite	1.0 (.9)	0.7	1 (.9)	70
3 melt	1.2 (1.2)	0.7	1 (.7)	77.89
3 composite	1.3 (1.2)	0.64	1 (.6)	88.92
Die	0.8 (.7)	0.55	1 (1.1)	35

* Note all data was fit to best first order model (i.e. C_2=1) in order to facilitate subsequent mathematics.

( ) Numbers in parenthesis represent best data fit regardless of model order.

WEIBULL FUNCTION FIT OF
SCREW 2 MELT SECTION INCL DIE

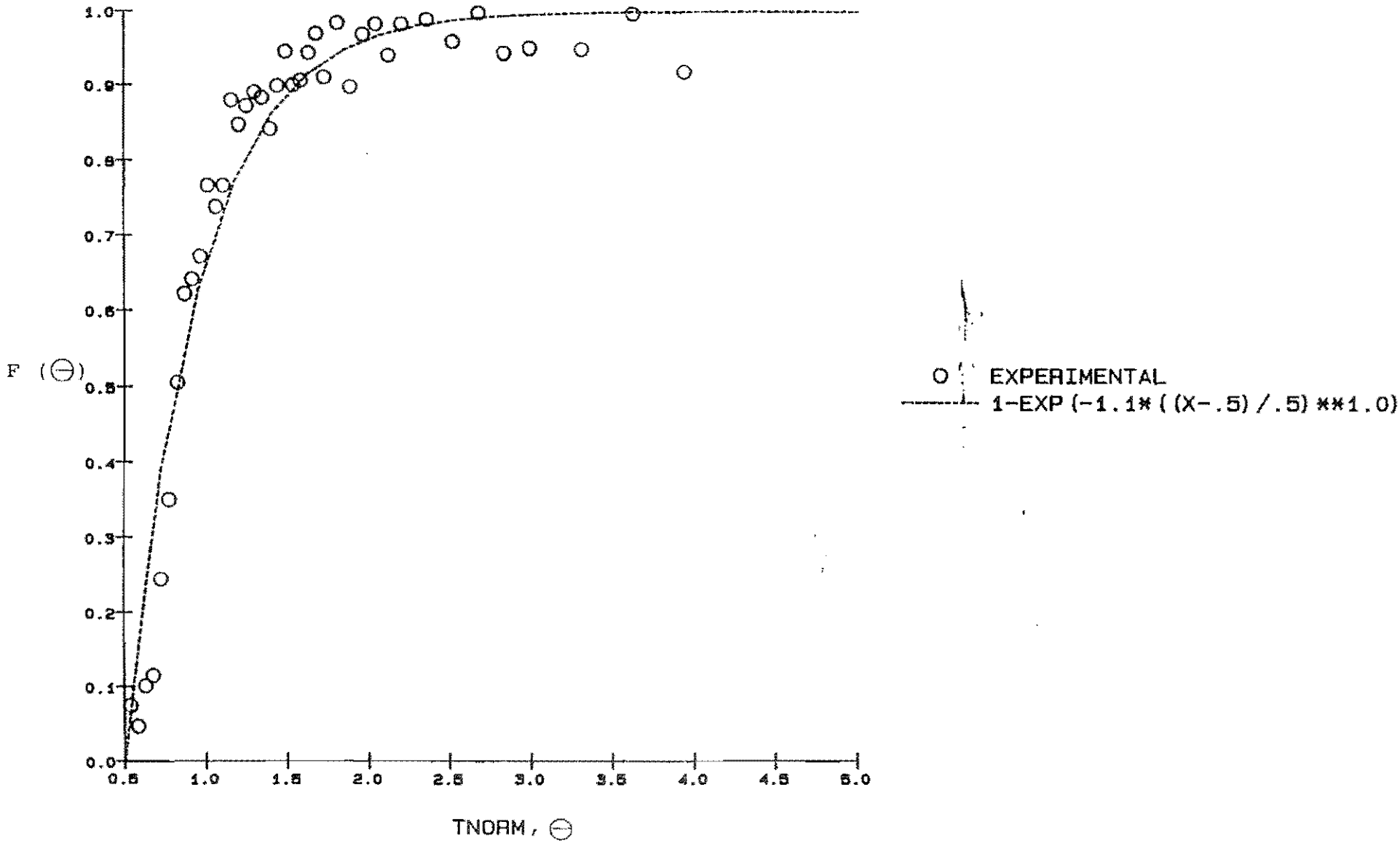


Fig 8a

DIE ANALYSIS

(From FEM analysis of Capacitance Die)

Lines represent boundaries of fluid elements with mean residence times as marked

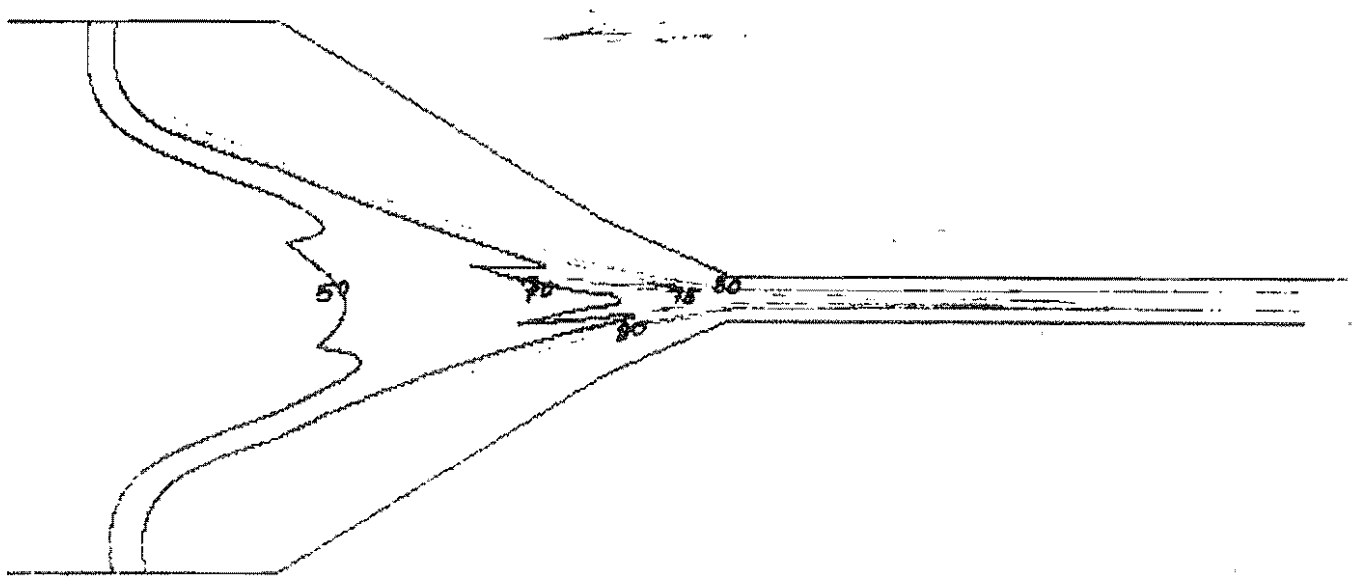


Fig 8b

MODEL FIT OF THE CALCULATED RESIDENCE TIME
DISTRIBUTION FOR THE DIE

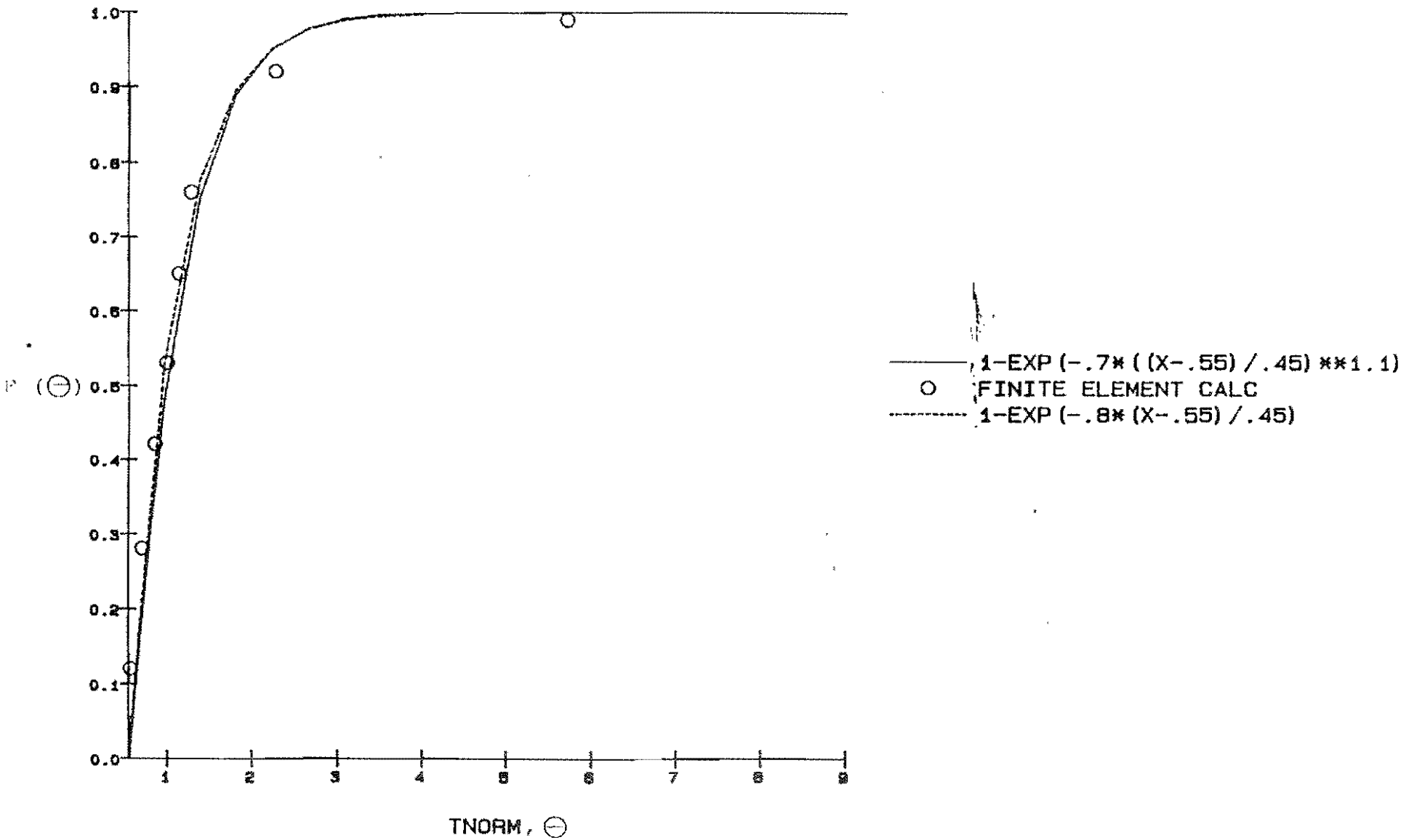


Fig 9a

Model Coefficients for
Cumulative Exit Age Distributions
for Extruder Parts

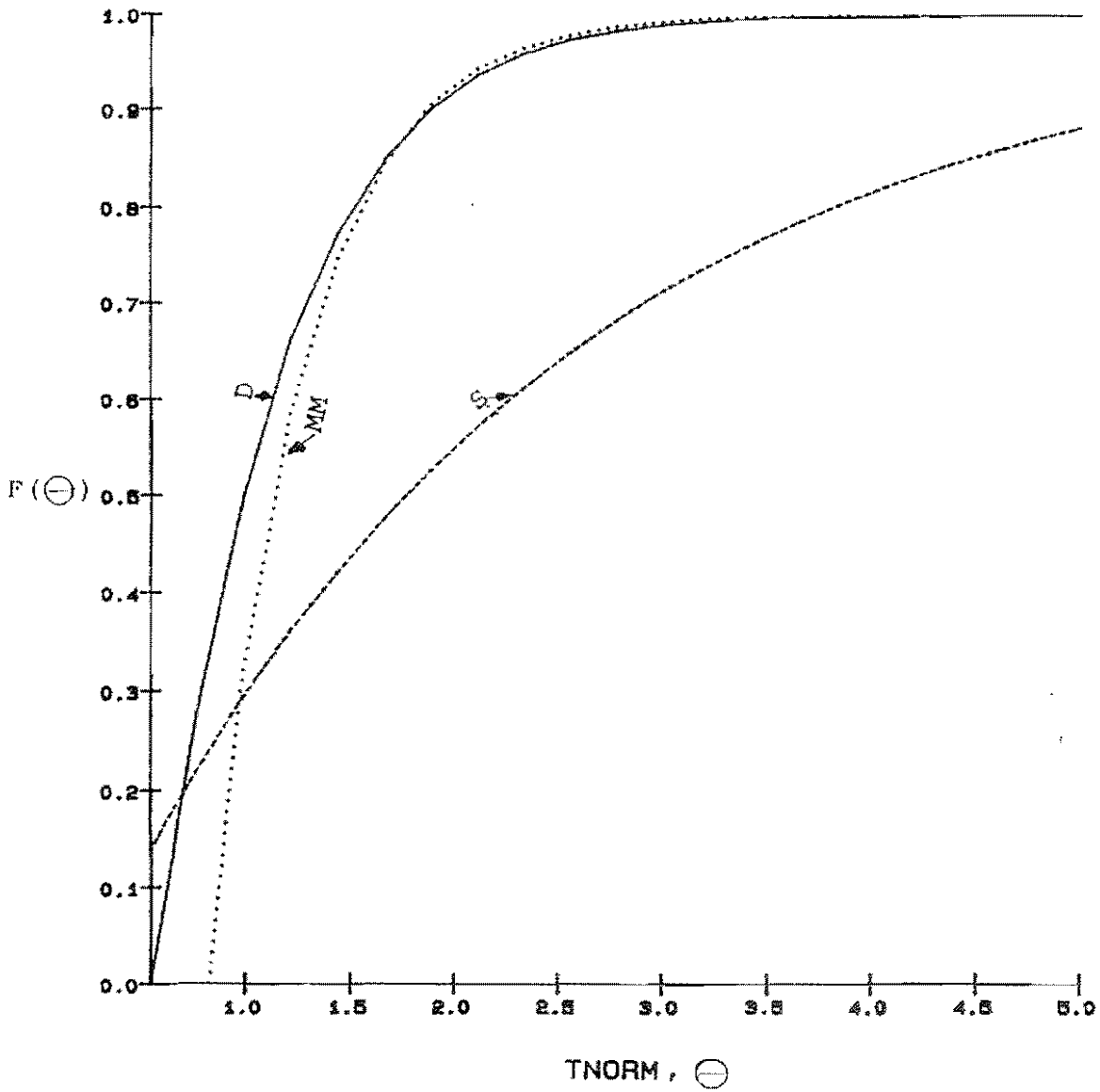
Screw	$\bar{t}$	P	C_1
1 solids	9.45	.223	.517
1 melt	23	.298	.557
2 solids	6.71	.259	.508
2 melt	28	.443	.542
3 solids	11.03	.217	.351
3 melt	43	.82	.398
Die	35	.55	.8

$$F(\Theta) = 1 - \mathrm{Exp}\left[-C_1 \left(\frac{\Theta - P}{1 - P}\right)\right]$$

$$F(t) = F(\Theta)\,\bar{t}$$

Fig 9b

DECONVOLUTION OF CUMULATIVE RESIDENCE
TIME FUNCTION FOR SCREW 3



1-EXP(-.7*((X-.55)/.45)**1.1)
1-EXP(-.398*(X-.82)/.18)
1-EXP(-.351*(X-.217)/.783)

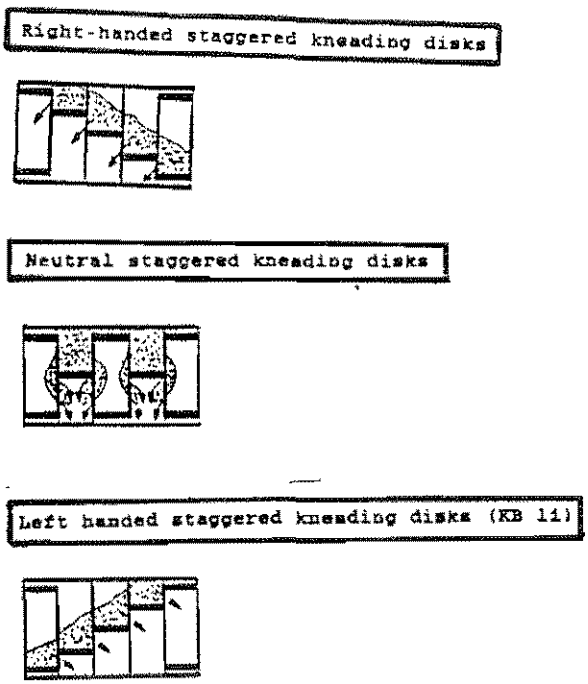
S - Solids transport and melting
MM - Melt mixing and pressurization
D - Die

Fig 10

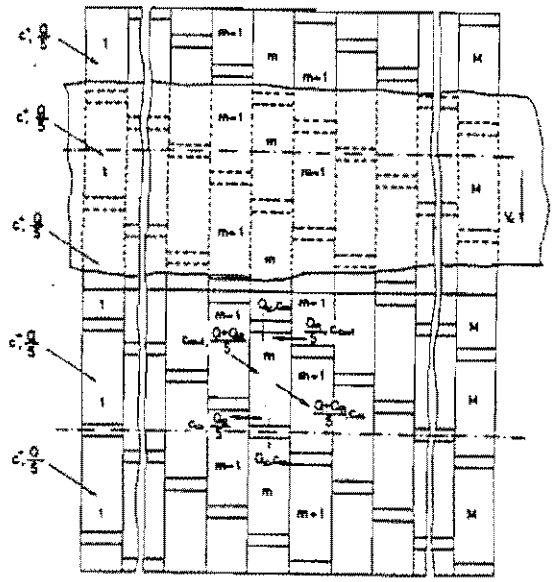
CALCULATED AND EXPERIMENTAL DAMPING OF A CYCLIC FEED COMPOSITION

Screw	Feed Period (Sec/Cyc)	Feed Amplitude (%F)	Product Period (Sec/Cyc)	Product Amplitude (%F)	Amplitude Ratio	Trans-port dead time (rad)	Calculated Amplitude Ratio	Calculated Transport dead time (rad)
1	144	11.6	130	7.1	.612	.97	.711	3.14
2	144	11.9	125	5.79	.487	1.50	.734	1.04
3	72	8.1	68	3.5	.432	3.6	.423	1.134
3	150	11.0	122	5.06	.460	2.06	.698	.802

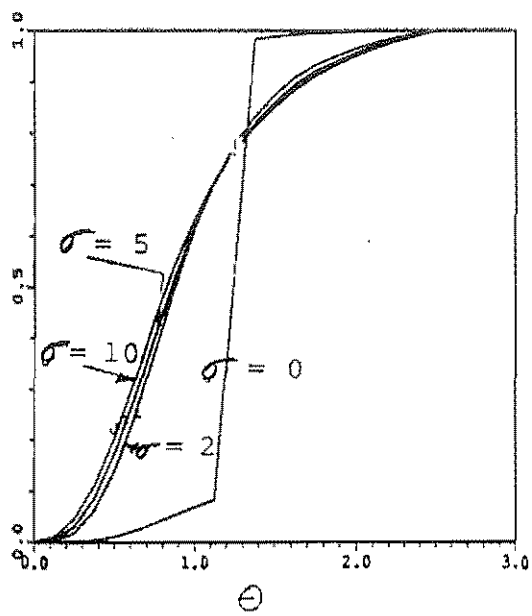
Flow in Kneading Blocks



a) Flow Representation in kneading blocks



b) Cascade Representation of flow in kneading blocks (for a 3-lobe ZSK after Werner)



c) Cumulative Residence Time Characteristic depending upon Reflux Ratio σ, (for 13, 2 lobed kneading discs, like the Melt Mixing Stack of Screw 3).

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Feed Variance Limitations for Co-rotating Intermeshing Twin Screw Extruders

Dedicated to the memory of our colleague, Dipl.-Ing. Heinz Herrmann, who through determined persistence, brought order to the art of twin screw compounding

The extent of feeder error to survive a plasticating compounding extruder is addressed in this theoretical and experimental study. Results of unit step and cyclic variation of tracer concentration were used to define the transfer function and damping ratio respectively. The frequency dependent damping ratio of cyclically varying tracer content in the feedstream was predicted for three screw configurations with fair agreement to experiment.

1 Introduction

Twin screw extruders are utilized as continuous mixers, reactors, and devolatilizers for viscous fluids and slurries. An important class of twin screw devices is the co-rotating intermeshing extruder, prized for its self wiping characteristic and ability to generate high shear stresses upon small process volumes. Because these continuous mixers can be operated in a starve fed mode, ingredients are often separately metered into the process. This practice has significant operating advantages such as reduced material handling, quick transition between products, reduced in-process storage, and enhanced possibilities for process control. Where accurate constituent concentrations are required in the product, the feeder errors are constrained by the limited backmixing capability of the mixer.

To be able to specify feeder accuracy criteria based upon product constituent variance limitations, one must understand the transport characteristics of the components through the mixing system. This is done either as a modelling exercise or through reduction of experimental residence time distribution (RTD) data.

A few analytical expressions for residence time in extruders have been developed [1, 2] but their application is limited to simple geometries, fluids, and without consideration of pressure flows. Flow simulation of complex mixer geometries by numerical techniques has been reported [3] but the analysis requires significant geometry simplification. Techniques for experimentally determining RTD for extruders and interpretation of results has seen substantial treatment in the literature. Golba [4] successfully measured the RTD of a twin screw compounder on line by measuring the relative dielectric constant of the tracer in the die. Many authors have used off line colorimetric techniques and some have used low grade isotope tracers.

Among others, Herrmann [5] has reported the effect of mixer geometry upon RTD for co-rotating intermeshing extruders. Todd [6] correlated his results to the single parameter Taylor diffusion model. Altomare and Ghozzi [7] used the two parameter fractional tubularity model. Potente [8] finds even better representation with a four parameter Gauss-Weibull function. Mixer response to transients in the feed streams for extrusion systems has not been widely reported. Balke [9] showed a methodology for predicting product concentration in extruded composites. He developed explicit predictions for first order mixers[1] with high frequency normally distributed feeder error.

This paper reports analysis of an experimental study in which three screw designs were characterized for their RTD's by the unit step technique. Only one fluid, one RPM, rate, and die pressure was analyzed. The melt mixing (MM) zone of each design was characterized in a separate experiment. The die RTD was numerically simulated. The feed system, extruder, and die are modelled as a serial network. The feed system was driven in a regular cycle at two periods for each screw and product tracer content was monitored. The experimentally observed damping is compared to theory.

2 Theory

The traditional method for predicting output from a composite system (e.g. feeder, extruder, die) is to apply the principles of linear[2] superposition and convolution. Linear-

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[1] First order mixer – A mixer whose residence time follows a first order differential equation ie.,

$m\frac{dy}{dt} + ny(t) = x(t)$ where m and n are coefficients, x(t) is the input (feeder) function and y(t) is the output (product) function.

[2] Linear superposition requires that each sub system is described by a linear differential equation, i.e. product composition is a function of time and inlet condition but not a function of itself nor derivatives of itself.

P-86

Feed Accuracy in Continuous Mixing Applications

by

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Feed Accuracy in Continuous Mixing Applications

Composite or blend performance depends above all upon formulation. The compostion variance is a function of error of continuous feeder and backmix capability of the continuous mixer. For instance, if the continuous mixer has a plug flow characteristic, the feeder cycle will survive the process undamped. If the continuous mixer tends towards an ideal mixer (batchlike), then the feed cycle is inconsequential as long as the feeder is capable of long-term averaged accuracy.

Real continuous mixers have a behavior intermediate between ideal mixer and plug flow. Figure 1 shows the probability function of cumulative exit age for step change in the feed signal for various pieces of equipment. Suppose the mean residence time of the single screw extruder is 1 minute. At 0 seconds a feeder disturbance happens. The effect is not sensed at discharge until 45 seconds later. The total disturbance is sensed at discharge according to the schedule in table 1 in the absence of additional disturbances in the same time frame. A feed disturbance of 2 seconds duration will show up at 35% of original intensity at discharge; 4 seconds at 48%, and so on. A 15 second feed disturbance will show 77% of the feed disturbance at discharge as shown later.

Loss in weight feeders try to operate at constant flow rate. Because of the cyclic behavior of flow rate from a screw discharge, and the motor speed cycles resulting from controller action, the loss in weight screw feeder displays an accuracy which is a function of sampling duration. Specifically, the accuracy is worse at short sampling times and low rates.

The error of an individual feeder is generally published as the 2S% error of the mean with a 30 or 60 second sampling time. For the sake of discreet extrusion feed, it has been shown above that the sampling time should be 15 seconds (or less) to avoid significant feed errors from affecting product formulation. If a loss-in-weight feeder runs long enough, the sample errors will be normally distributed about the mean. In this case it is more correct to calculate % error at a specified confidence level. An example of the procedure is included as Table 2.

If several feeders are operating independently on an extrusion line, each with normally distributed errors, then the sample variance of the composite system can be predicted according to the theory of propagation of error. A sample calculation is included as Table 3. As expected, the variance of any species in the product is greater than the individual variance of that species' feeder.

The discharge concentration of any species is a result of the convolution of feeder rate function and extruder residence time.

$$W_A(t) = \int_0^t W_A(\alpha)\, E\,(t - \alpha)\, d\alpha$$

where - $W_A(t)$ = Discharge concentration function of component A w.r.t. time.
$W_A(\alpha)$ = Feeder concentration function of A component w.r.t w.r.t time.
$t - \alpha$ = Non dispersing time delay between feed and dis charge time until first tracer show.

In the lucky event that extruder mixing is first order[1] and the feed cycle is sinusoidal, the extruder discharge concentration of any species can be determined from a Bodie plot.

$$AR = \frac{1}{(1 + W^2\tau^2)^{1/2}}$$

where: AR = amplitude ratio of discharge signal/input signal

W = feeder cycle,

τ = characteristic time for extruder[2]

Figure 2 shows the superimposed input and output variance for a ZSK extruder at 2 feeder cycle frequencies. The fast cycle trace is slightly better damped than the slow feed cycle but the screw had a low backmix characteistic.

Feeder Evaluation (screw loss-in-weight type)

Feeder performance depends upon:

a) Hopper discharge characteristics (shape, finish, agitators, stirrers, intrometers).
b) Screw delivery system (single, twin, solid, hollow, tube finish, clearance, tip shape, tube pins).
c) Scale sensitivity.
d) Upset logic (reload, vibration).
e) Controller update.
f) Controller logic.
g) Feeder sizing for application.

The characteristics of tested feeders are included as Table 4.

---

1 Can be described by 1st order linear ordinary differential equation ~~No higher powers of time appear in the cumulant expression~~.

2 Characteristic time, for a cumulant expression of the type

$$F = 1 - \exp\left(-C_1\left(\frac{\Theta - P}{1 - P}\right)\right), \quad \tau = \frac{1 - P}{C_1}\,\bar{t}$$

There are two basic scale types:

a) Damped vibrated string with frequency based output signal. These scales are digital and have update and resolution limitations. The mechanism is compact, rugged, and reliable.

b) LVDT with amplified output signal for low flexure. Analogue scale with practically infinite resolution.

From the data in Table 5, several conclusions can be drawn:

1) A successful feeder candidate can be operated to good accuracy in volumetric mode provided incompressible well mixed feeds and free flowing behavior.

2) Single screw feeders can perform as well as twin screws, unless:

   a) Hopper flow conditions require the larger feed opening of a twin screw,.

or,

   b) The feeder is required to operate at low speed, where the twin screw is less prone to slugging than the single screw.

3) Belt feeders are not superior feed devices especially at low sampling times.

4) Feeder sizing is critical for accuracy.

Table 1

Schedule of discharge effect caused by
step charge feeder disturbance according to figure 1
Single Screw Extruder 60 sec mean residence time

Time (sec)	% of Disturbance sensed
0	0
45	0
47	35
49	48
51	58
53	62
56	64
58	72
60	77
75	87
90	91

From: Tadmor, Klein, Eng Principles of Plasticating Extrusion
Van Nostrand (1970) p 347

Fig 1 - Ref 4

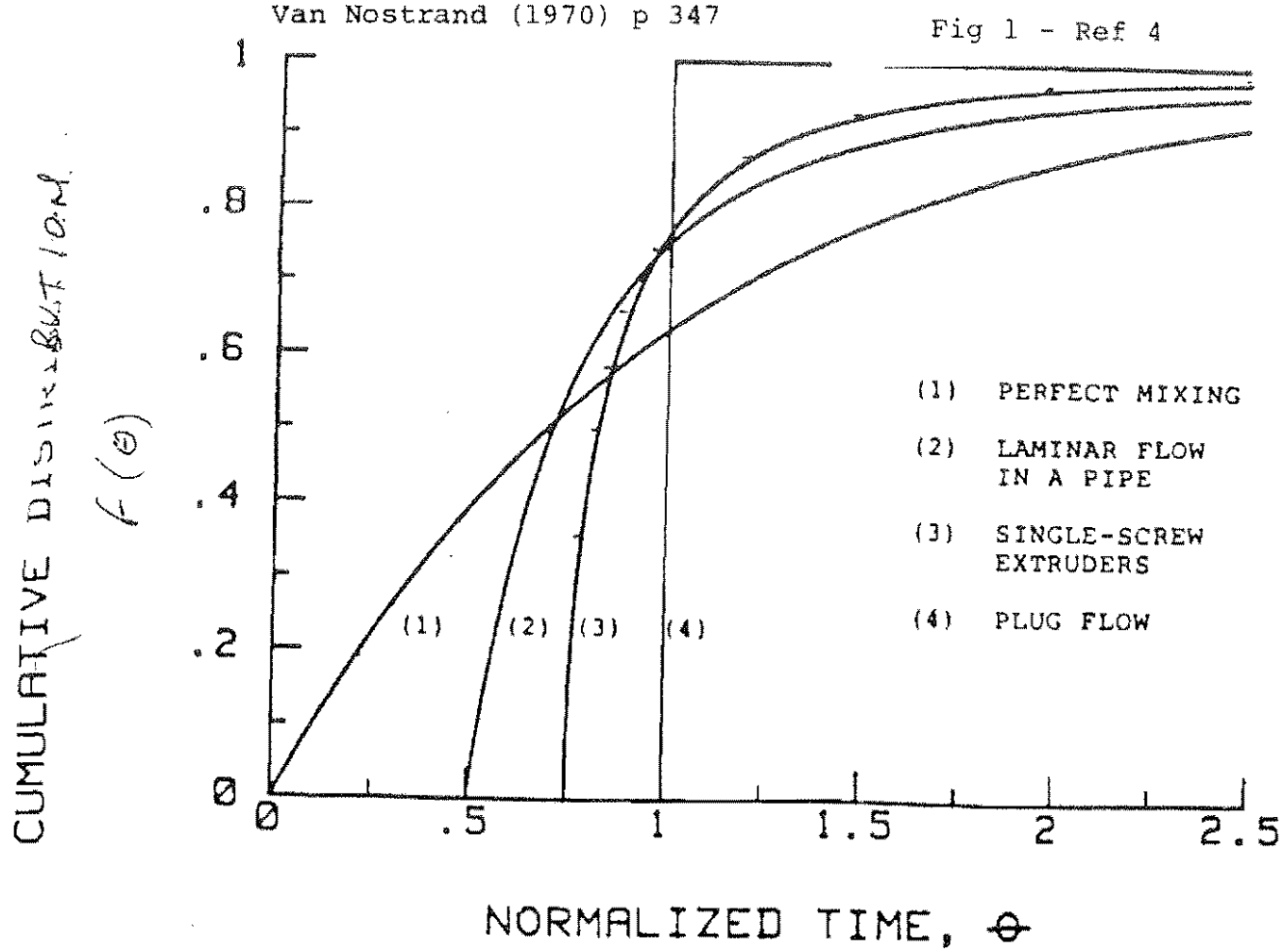


Table 2

Sample Error Calculation for loss-in-weight feeders:

Feeder Type:	Brabender DBW H2A DDSR 40-120
Feed Material:	Ammonium Sulfate, coarse 75 pcf
Screw:	Twin pigtail, 45mm pitch
Setpoint:	200 pph.
Sampling time:	5 sec.
PID:	5,3,0
% motor speed:	10.3
Sample rates, [10] g/sec.	25.36
	24.00
	26.47
	24.89
	23.95
	24.40
	22.84
	25.26
	24.67
	26.57
Average	24.84
Sample deviation	1.15
Error at 95% C.L.	± 0.82

$$\bar{x} = \sum^{n} \frac{x_i}{n}$$

$$S = \left[\sum^{n} \frac{(x_i - \bar{x})^2}{n-1} \right]^{\frac{1}{2}}$$

t at 9 degrees of freedom = 2.26

$$v = \frac{ts}{\sqrt{n}}$$

95% C.L. = 1.96 σ

σ = standard deviation of parent population.

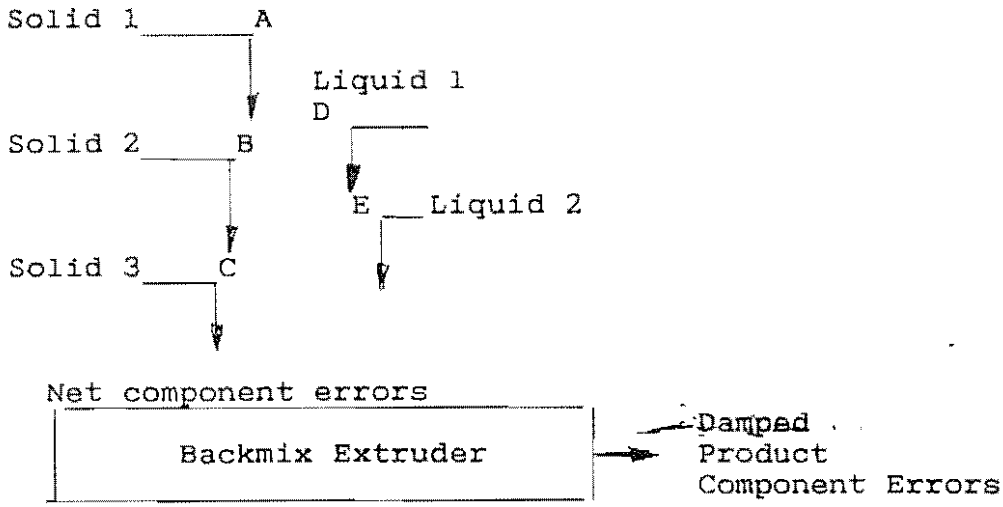
Errors:

2S of mean..... 9.3%
of setpoint..... 9.1

95% C.L. error of mean.. 3.3 %
of setpoint..... 4.8

Table 3

Error Propagation of Individually Fed Extrusion System



The weight fraction of component A in the feed is

$$WA = \frac{FA}{F_A + F_B + F_D + F_E + F_C}$$

WA = weight fraction A
FA = mass feedrate of A

The fluctuation of A in the feed stream depends upon the error in each of the feeders and can be expressed by propagation of error.

$$S_{WA}^2 = \left(\frac{\partial WA}{\partial FA}\right)^2 S_{FA}^2 + \left(\frac{\partial WA}{\partial FB}\right)^2 S_{FB}^2 + \left(\frac{\partial WA}{\partial FC}\right)^2 S_{FC}^2 + \left(\frac{\partial WA}{\partial FD}\right)^2 S_{FD}^2 + \left(\frac{\partial WA}{\partial FE}\right)^2 S_{FE}^2$$

where S_{WA} is the standard deviation ~~in component feeder A~~ of component A in the feed stream

from math tables $\frac{\partial}{\partial x}\left(\frac{u}{v}\right) = \frac{1}{v}\frac{\partial u}{\partial x} - \frac{u}{v^2}\frac{\partial v}{\partial x}$, $u = FA$, $V = F_A + F_B + F_C + F_D + F_E$, $x = a$ of F_A, F_B, F_C, F_D, F_E

Reducing

$$\left[\frac{S_{WA}}{WA}\right]^2 = (1-WA)^2 \left[\frac{S_{FA}}{FA}\right]^2 + \left[\frac{S_{FB}}{FB}\right]^2 W_B^2 + \left[\frac{S_{FC}}{FC}\right]^2 W_C^2 + \left[\frac{S_{FD}}{FD}\right]^2 W_D^2 + \left[\frac{S_{FE}}{FE}\right]^2 W_E^2$$

For a formulation with randomly cycling independent feeders whose deviation has been measured by a method of table 2, component error propagation as follows.

Component	Set Point Rate (pph)	Feeder Deviation (pph) (10 Sec Sample, 95% CL	Component Error in Feeedstream 95%CL
Solid 1	25	± 2.3	± 1.89
Solid 2	25	± 2.3	± 1.89
Solid 3	38	± 2.0	± 1.76
Liquid 1	10	± 0.3	± 0.475
Liquid 2	2	± 0.1	± 0.120
	100		

Sample Calculation:

$$\left[\frac{S_{WA}}{WA}\right]^2 = \left[\frac{S_{WA}}{.25}\right]^2 = (1-.25)^2\left(\frac{2.3}{25}\right)^2 + .25^2\left(\frac{2.3}{25}\right)^2 + .38^2\left(\frac{2.0}{38}\right)^2 + .1^2\left(\frac{.3}{10}\right)^2 + .02^2\left(\frac{.1}{2}\right)^2$$

$$S_{WA} = .0189 = \pm 1.89\%$$

Table 4

Characteristics of loss-in-weight feeders

1. Brabender DBW H2 A DDSR 40-120

a) Hopper - Polished steep stainless. 2 or 4 blade agitator 7 cuft.
b) Twin screw delivery 40 Ø. Hollow or trapezoidal pitch screws. Stainless tube. Optional pin barrel discharge. Self emptying hopper designs. 4.24 cuft/hr. maximum.
c) Scale capacity adjustable by lever arm. 30 and 60Kg. Resolution 120 K counts. Minimal weighment 0.25g. Scale type: damped vibrating wire. Dashpot paralleled. Hanging cantilevered suspension.
d) Controller Congrav
e) Control logic PID accessable, program controlled. Full electronic controller faceplate programmable.
f) Full range screw RPM.
g) Number of apparent discharging channels - 3.
h) Operator available tuning:
   1) Scale sensitivity
   2) PID settings
   3) Scan time
   4) Deviation tolerance
   5) Vibration/overload protection
   6) Max/min screw speeds

K-Tron LWF T-35-B

a) Hopper - polished, steep or conical, stainless. 2 or 4 blade agitator.
b) Twin or single screw discharge (interchangeable hoppers). Hollow or whirled screws, various pitches. Also hollow auger with tapered root. 150 or 300mm tube length. Self emptying hopper design (0.2 - 40 cuft/hr).
c) Damped vibrating wire weigh mechanism. Scale resolution 120K counts. Capacity: 30 Kg. Minimum weightment: .054g. Direct scale mount suspension.

d) Controller 7100 cMos controller with Backboard pin adjustable programming. (Alternate: K-10 PID auto tuning controller).

e) Full motor speed 1800 RPM. Three interchangeable gear boxes, (A fast, B mid 6.742:1, C slow)

f) Operator available tuning:
   1) Mass flow span and zero (S4)
   2) Gain (JB1) 3 position
   3) Motor speed span (JB3)
   4) Deviation tolerance (JB4), 1-10 (1 sensitive)
   5) Mass flow signal damping (JB2)
   6) Ramp speed (JB1)

Table 4 (continued)

3. Acrison #403-105 Z

a) Hopper - vertical walled, polished stainless

b) Single screw delivery. Square channel or hollow auger (1 3/8" Ø, 75mm pitch hollow). 6" intromitter with reversing and clips. Intromitter RPM 0.5 of screw. Screw diameter interchangeagle .4-14 ft^3/hr.

c) Six point hopper suspension via cruciform flexures from frame. Linear variable differential transformer weight resolver. Dashpot paralleled. Scale capacity 150 lbs., resolution minimal weightment .065g.

d) Controller Microdata 403.

e) Screw speed 104 RPM max.

f) Operator available tuning:
   1) Gain
   2) Motor speed span
   3) Scale span
   4) Deviation mode timer
   5) Deviation tolerance

g) Scale sensitivity 1048000 counts.

Summary of feeder performance

Feed Material: Crystalline Ammonium Sulfate, 325μ mean particle
75 pcf bulk density, incompressible, free flowing

Feeder	Setpoint (pph)	Sample Time (sec)	% Motor Speed	Average rate (pph)	Error (% mean) 2 S	95% C.L.
K-Tron T-35	Volumetric	10	50.1	365.95	2.0	0.7
25mm pitch	365	10	49.8	363.89	1.4	0.5
2 flight	365	5	49.8	365.00	7.4	2.6
solid	75	10	9.8	75.41	2.1	0.7
B gear	75	5	9.8	76.52	5.6	2.0
K-Tron S-200	Volumetric	10	10.2	204.98	3.1	1.1
600mm pitch	200	10	10.2	205.45	1.6	0.6
pigtail,						
50mm Ø						
B gear						
Brabender	Volumetric	5	50	840.77	6.5	2.3
DBW H2A DDSR	200	10	10.5	198.95	6.2	2.3
40/120	200	5	10.5	196.97	9.3	3.3
(pigtail	45	10	2.0	44.58	14.5	5.3
series)	45	5	2.0	45.99	41.4	14.8
	45	30	2.0	45.28	3.5	1.2
Acrison	Volumetric	10	50	268.02	1.8	0.6
	250	10	46.6	252.24	1.9	0.7
	250	5	46.6	255.49	2.4	0.9
	45	10	8.7	45.36	17.5	7.0
	45	5	8.7	47.02	11.5	4.0
K-Tron GF-6	Volumetric	10	50	58.2	3.5	1.2
Belt 6"	52	10	50	51.78	1.8	0.6
	44	5	35.6	44.17	5.7	2.0

Feed Material: Spherical Aluminum powder, 5μ mean particle
120 pcf bulk density, compressible, fluidizable

K-Tron T-35	Volumetric	10	35	17.60	2.7	1.4
3/4" hollow	"	30		17.68	1.8	0.9
screw	"	10	25	7.85	2.0	1.0
	"	5		8.01	8.0	4.0

Feed Material: Non spherical Aluminum powder, 5 mean particle
120 pcf bulk density

K-Tron T-20 LWF	19	10	22.9	19.03	1.7	.4
B gear	19	5	22.9	19.06	4.2	1.5
10mm pitch,	19	30	22.9	18.98	1.4	0.5
2 flight solid						
screw						

Feed Material: TiO_2 powder agglomerating, 37 pcf bulk density

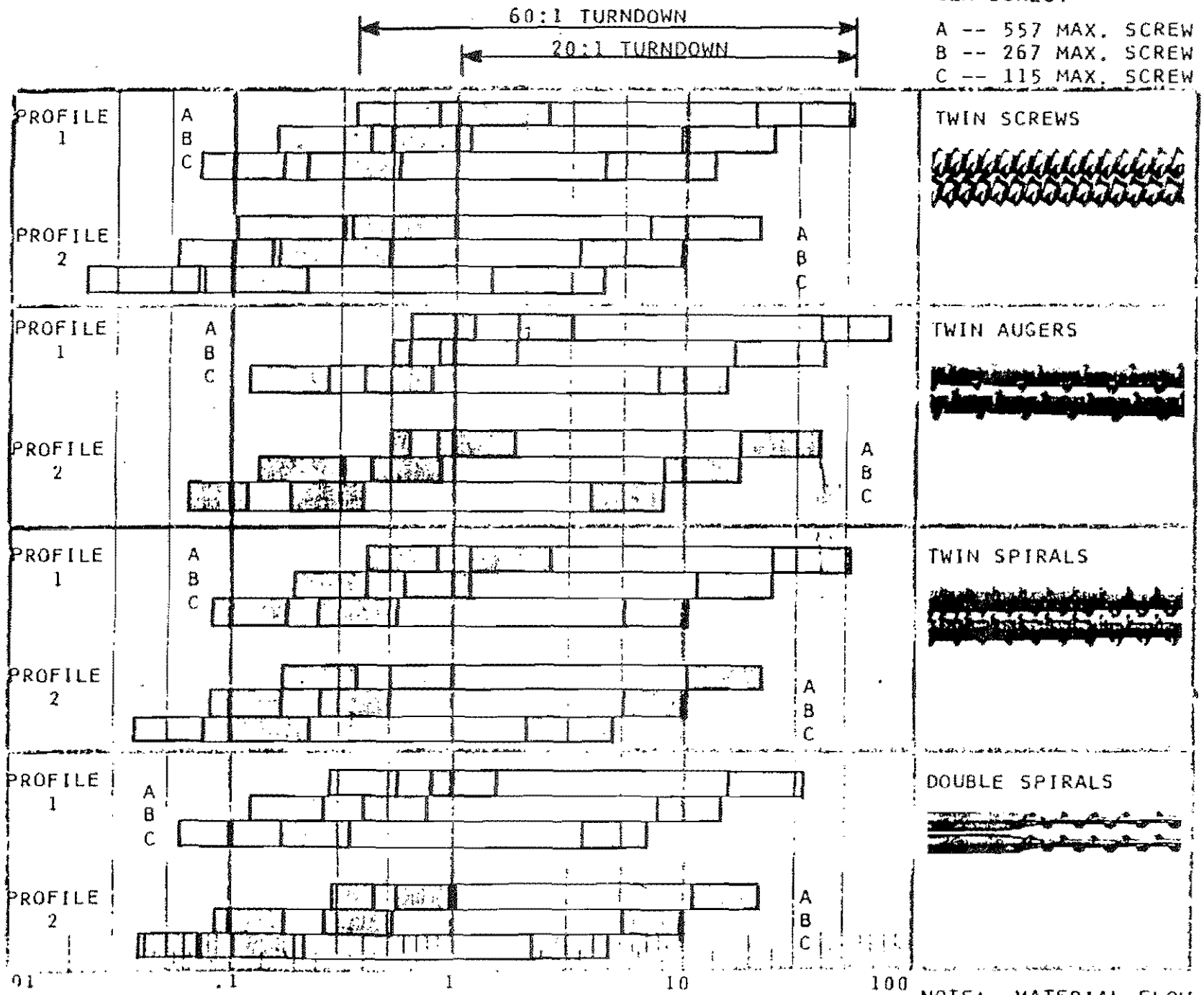
K-Tron LWF	60	15		59.68	5.56	1.2
3,200, 31mm		30		59.66	4.46	1.0
closed flight		60		59.68	3.26	0.7
A pitch, A gear	10	15		9.99	18.19	4.1
single screw		30		9.99	10.37	2.4
		60		10.00	5.78	1.3
K-Tron LWF	11.02	15			2.88	
S-20-7110	26.46	15			2.8	
twin screw	66.15	15			1.76	
22 samples						
K-Tron LWF-3	11.02	15			3.82	
FB-130, 3"	26.46	15			2.8	
weigh belt	66.15	15			4.00	
Acrison DIW-	11.02	15			8.0	
K2-75	39.69	15			4.2	
single screw	44.10	15			4.8	
	66.15	15			4.0	
Acrison 405-10-	10	15	34	10.14	4.0	0.9
40-BDP 1.0 C						
Single screw						
3/4", 1" tube						
30 samples						

K-TRON CORPORATION

VOLUMETRIC RATES 155

GEARBOXES:

A -- 557 MAX. SCREW RPM
B -- 267 MAX. SCREW RPM
C -- 115 MAX. SCREW RPM



NOTE: MATERIAL FLOW IN SHADED AREA DEPENDENT ON MATERIAL CHARACTERISTICS

9/83

4.111R

AOT

A Comparison of Continuous and Batch Processed Double Base Propellant

Presented in Cooperation with CELERG and SNPE, St. Medard France

Agenda

- Background
- Technology Demonstration
  - Test Plan
  - Results
- Conclusion

Background

- Manufacture of Double Base Propellant in the US has Changed Little in the Last Three Decades
  - Developments in Propellant Technology Have Focused on Composite Propellants
- Not True of European Propellant Industry
  - Significant Improvements Made in Formulating, Processing and Inspection of Double Base Propellants

Background cont.

AOT

- AOT Tasked With Identifying Technologies that Could Provide Indian Head With Improved Production Capabilities

  Working With CELERG and SNPE, Several Technologies Demonstrated

- Compared Propellants Produced in Continuous and Batch Process

Test Plan

AOT

- Objective

  Direct Comparison of DB Propellant Produced in Batch and Continuous Processes

- Approach

  Produce 20 Grains By Each Process
  - Identical Raw Materials
  - Propellant- Similar to AA2
  - Grains- Similar to MK90

Test Plan cont.

- Test:
  Physical, Chemical and Mechanical Properties

- Fire
  4 Grains From Each Process

  - 2 Hot and 2 Cold

Batch vs Continuous Process

Step	Batch	Continuous
NC/NG Paste Mix	Required	Required
Drying & Rolling	Two Mills, Small Batch	One Mill, Continuous
Slitting	Required	Not Required
Carpet Rolls	Required	Not Required
Preheat	Required	Not Required
Press Feed	Manual	Automatic
Extrusion	Ram Press	Twin Screw Extruder

Continuous Process Advantages

AOT

- Cost

  Less Capital Equipment
  Requires Less Space
  Fewer Operators
  Reduced Waste

- Safety

  Reduced Quantities of Propellant in Machinery
  Reduced Personnel Exposure

Results

- HoE

  Continuous 1.0%< Batch
  - Possibly Due to Higher Moisture of Continuous Propellant

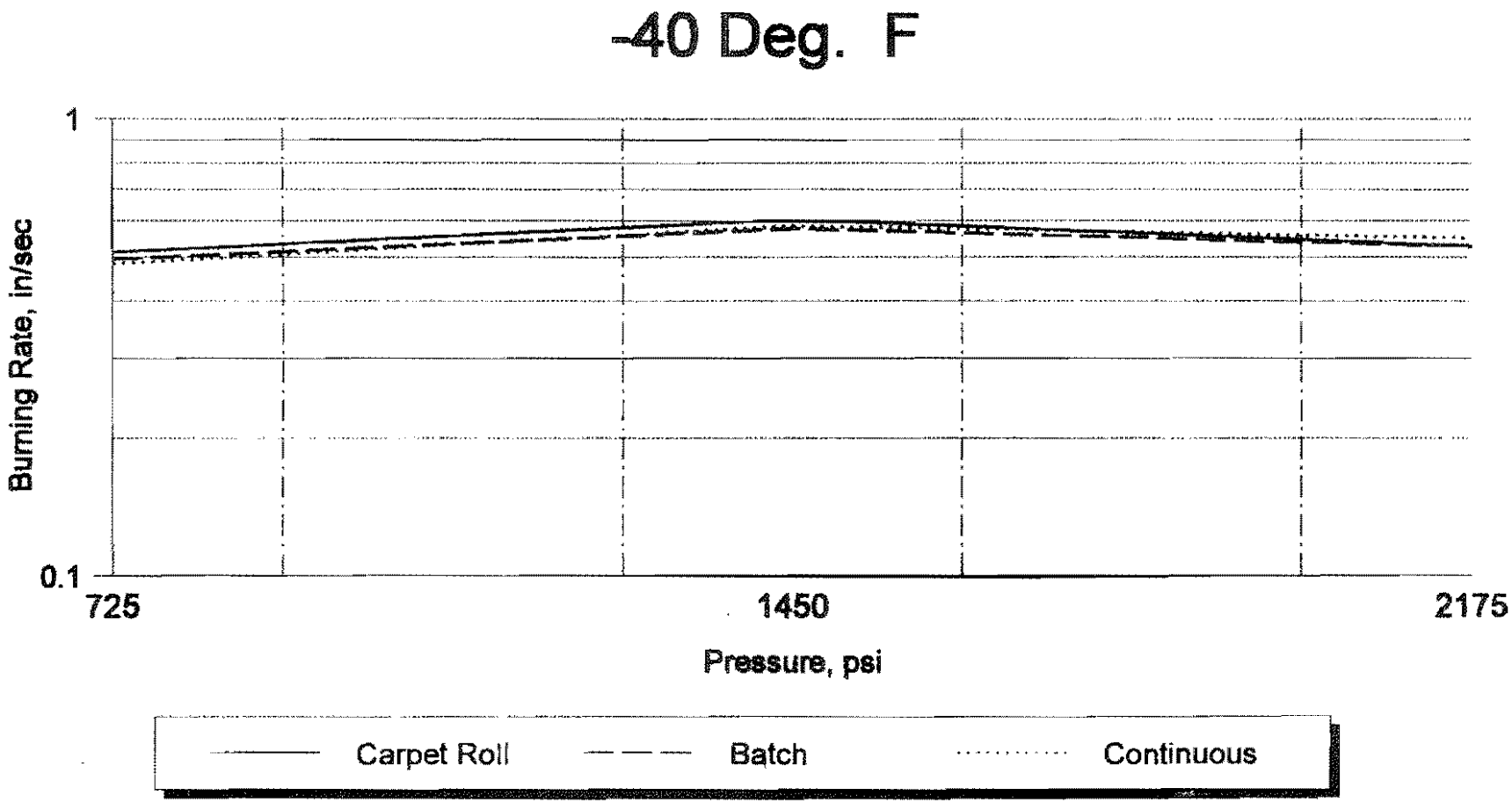
- Burning Rate

  No Significant Differences Between Carpet Roll, Batch or Continuous Grains
  - Continuous Propellant is Slightly More Temperature Sensitive

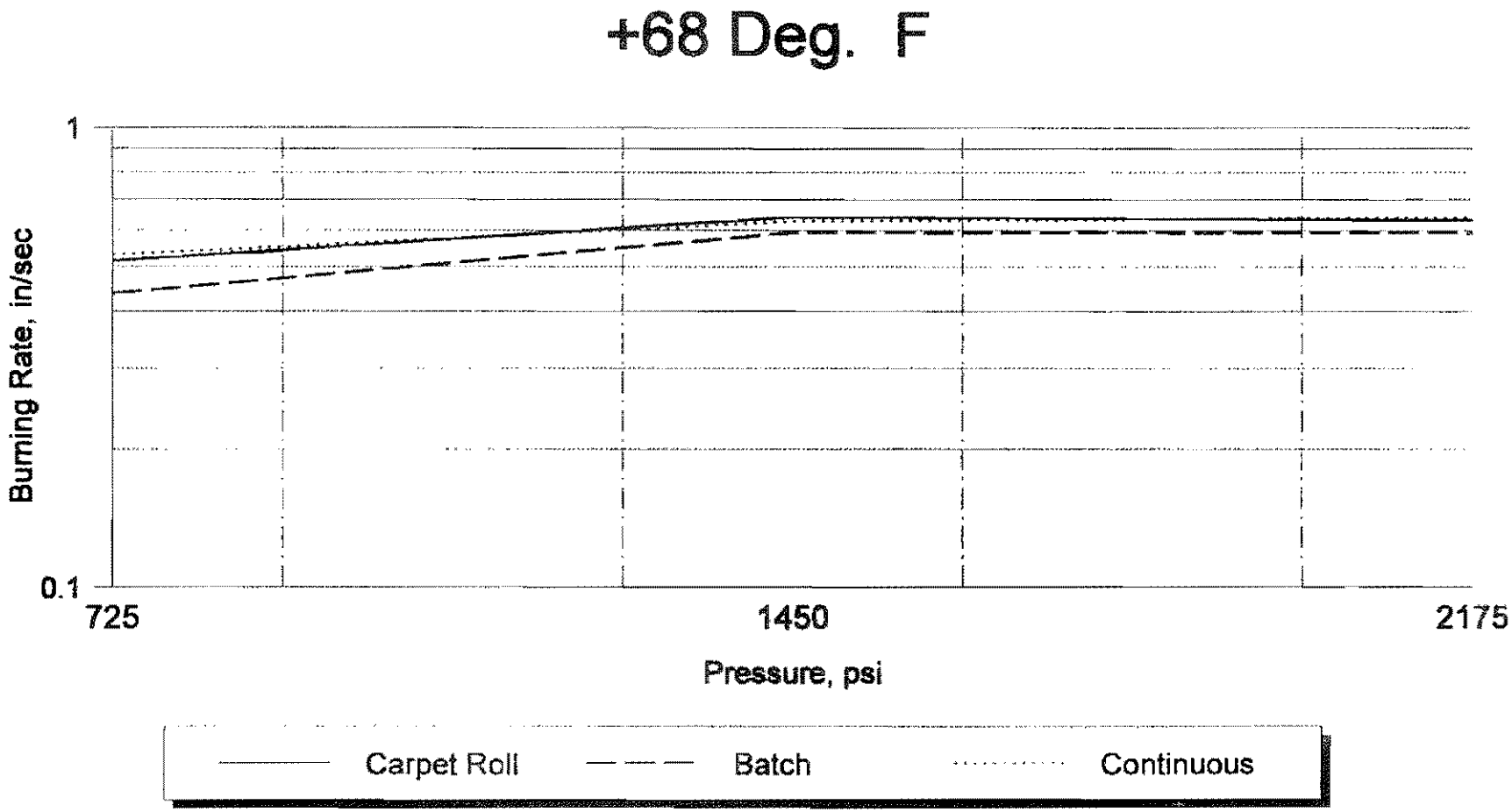
Physical and Chemical Data

Test	Batch	Continuous
Hot , cal/gm	1000	991
Moisture, %	0.46	0.57
Stabilizer, %	1.89	1.81
Density, lb/in3	0.0592	0.0592

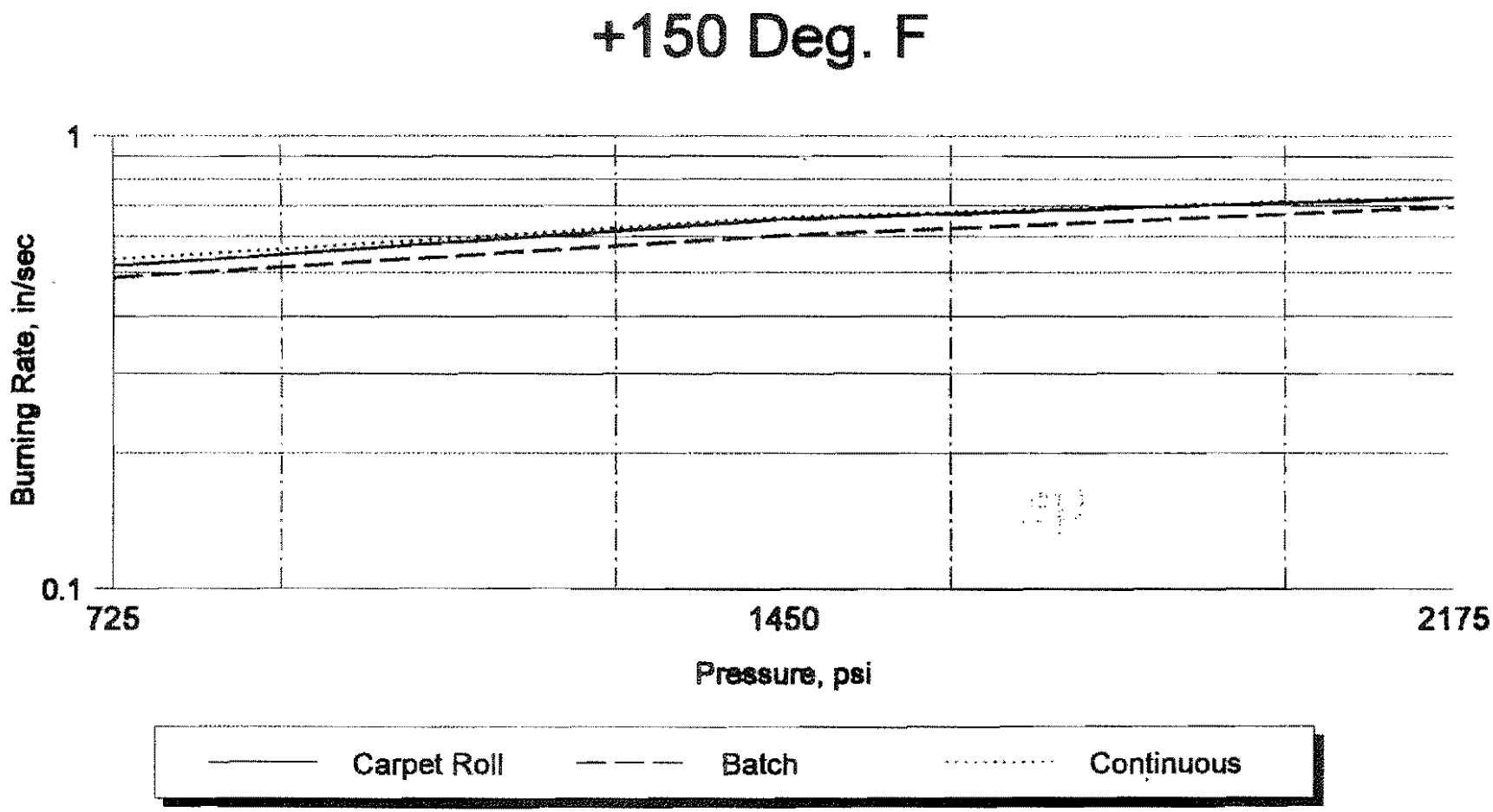
Burning Rate



Burning Rate



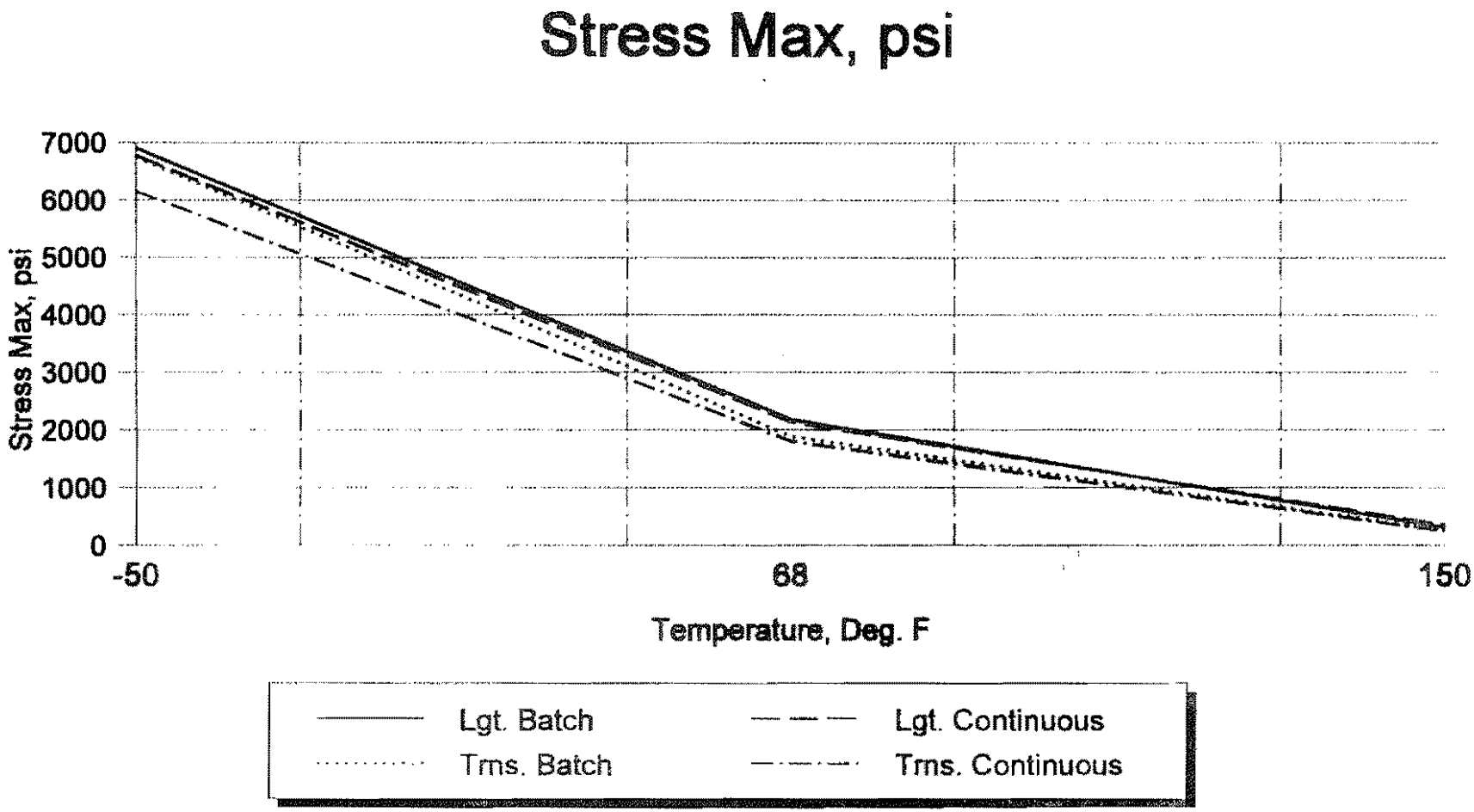
Burning Rate



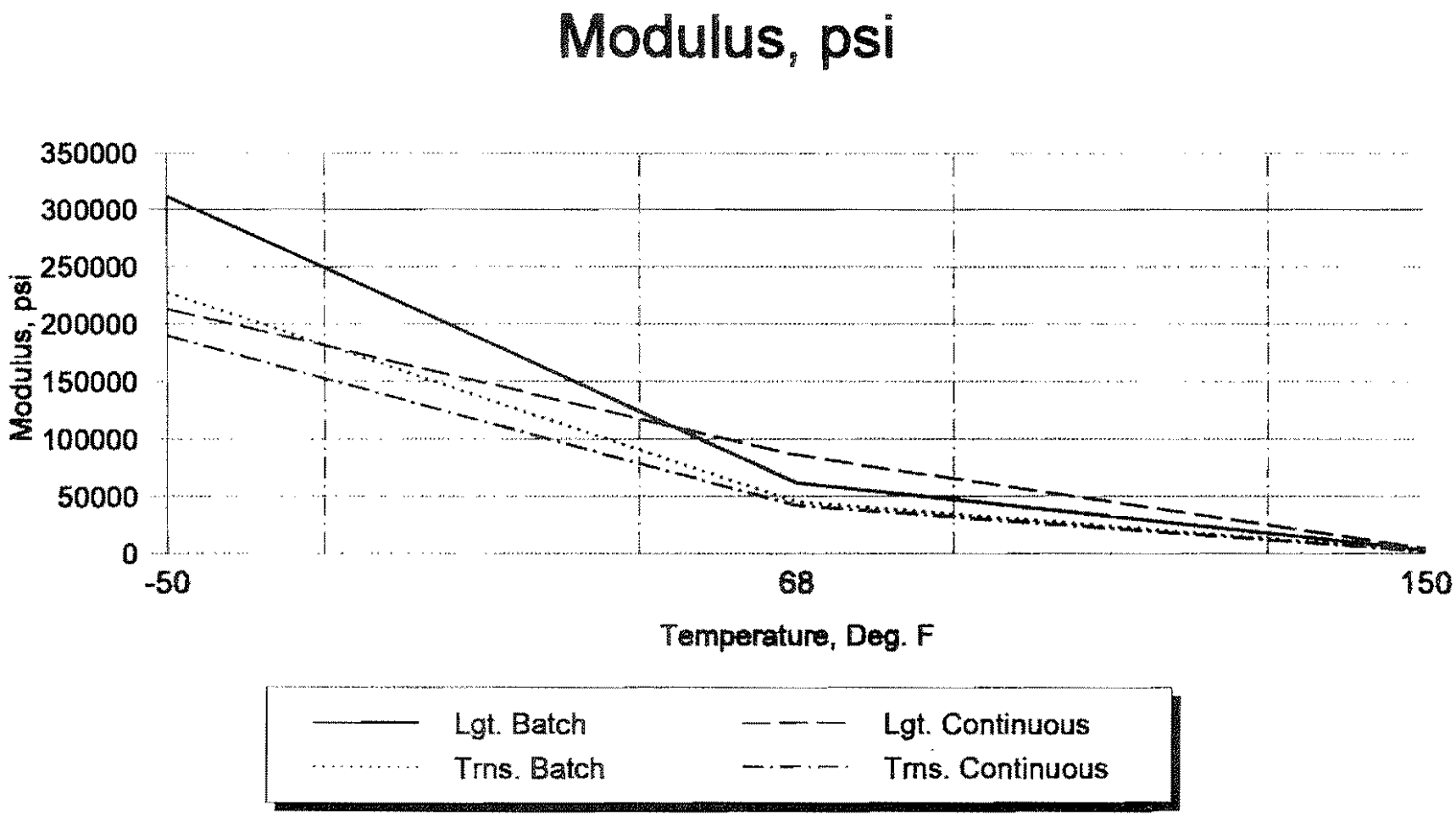
Results cont.

- Mechanical Properties
  - Measured in Longitudinal and Transverse Directions
- No Significant Differences Between Batch or Continuous Grains
- Longitudinal and Transverse Samples Exhibited Some Bias
  - Bias Most Pronounced in Strain

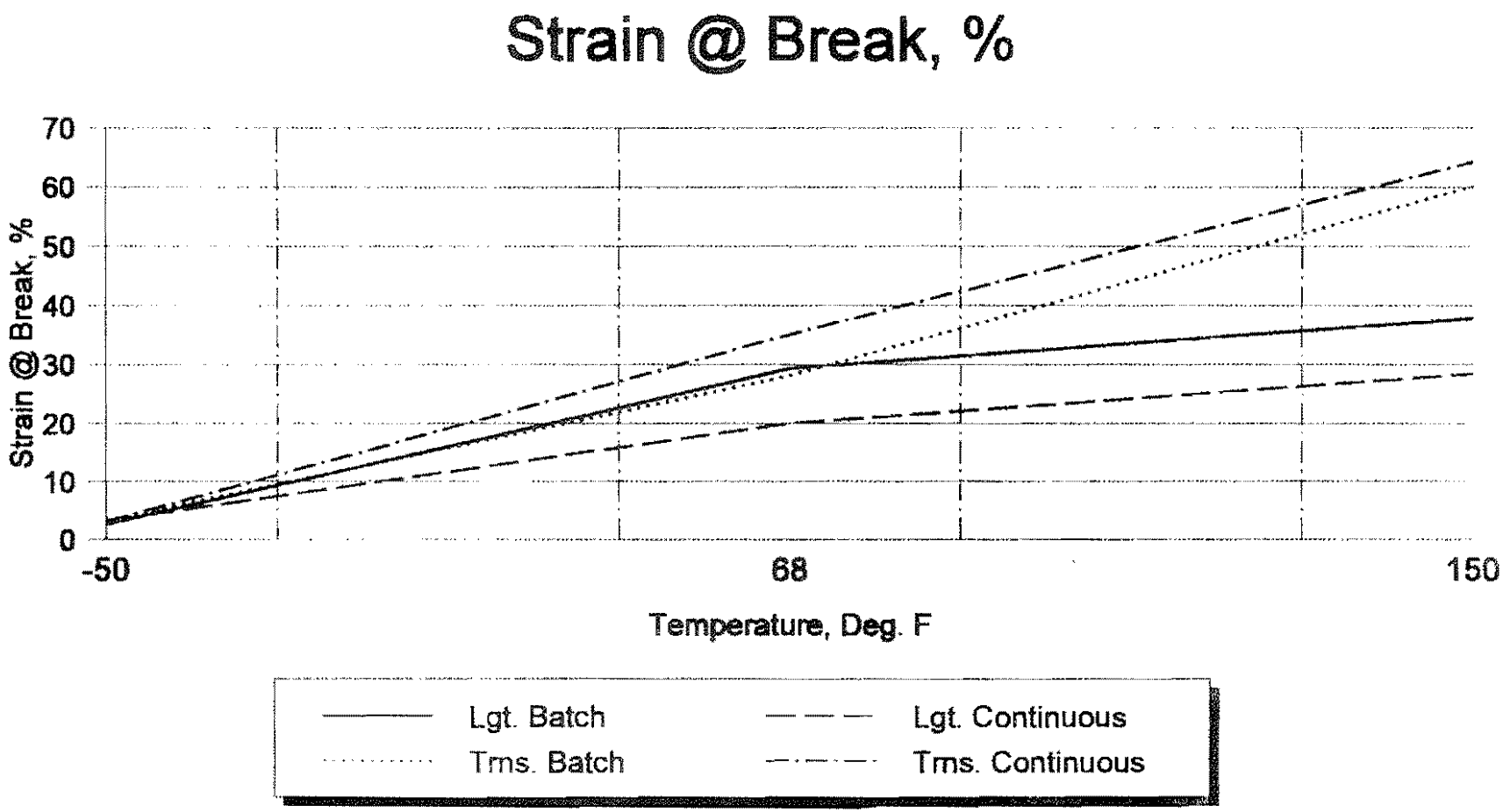
Mechanical Properties



Mechanical Properties



Mechanical Properties



Results cont.

- Ballistics

  Batch and Continuous Data Very Similar

  - Small Differences in Total Impulse and Hot Action Times are Probably Due to Differences in Propellant Weight and HoE

Motor Firing Data

AOT

Batch and Continuous Grains

Process	-50 Deg. F				+150 Deg. F			
Process	Batch	Batch	Cont.	Cont.	Batch	Batch	Cont.	Cont.
Grain#	2.1	2.8	6	9	2.2	2.15	13	16
Prop. Weigh Lb	7.28	7.32	7.19	7.25	7.29	7.33	7.25	7.25
Total Impuls Ft lb/sec	1538	1551	1525	1533	1592	1595	1573	1573
Action Time sec	1.18	1.2	1.2	1.22	1.02	1.04	0.96	0.96
Avg. Pressu psi	1427	1375	1346	1330	1674	1648	1730	1745
Specific Imp sec	211.2	211.8	212	211.5	218.5	217.6	217	216.9

Conclusion

AOT

- Continuous and Batch Processed Double Base Propellants Are Equivalent

  Properties & Performance

- Continuous Processing Offers Cost and Safety Advantages Over the Traditional Batch Process

  For High Volume Production Requirements

  - Example 2.75" Rocket

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September 21, 1995

AOT MEETING

The following is summary of LT Industries slide presentation. It is intended to convey LT's overall capabilities in a variety of fields. LT has experience with numerous types of polymer applications (including explosives) in addition to applications touched on in this presentation.

1. LT Industries Rockville, MD
2. A picture of the Quantum 1200 bench top/laboratory instrument. A full range scanning spectrophotometer.
3. A graphic demonstration of the versatile of the Q1200. Configurations, ranges, types of materials it is able to measure, closed loop operations, etc...
4. Detail of Quantum series spectral range(s). (from 400 to 2400 nm)
5. Detail on various modes or measuring techniques. (Transmission, Reflectance, Transflectance)
6. Math programs/techniques available through LT Industries. (MLR, PLS, PCR, Descrim.)
7. A listing of the major markets LT currently participates. (Petro/Chemical, Pharmaceutical, Textile, Food, Dairy, etc...)
8. A description/breakdown of applications in a market. One of the examples in the drug or pharmaceutical industry.
9. A description/breakdown of applications in a market. One of the examples in the textile industry.
10. Details a Q1200/2000 and it's industrial capability. (EX: Class 1, Div 1, group C-G)
11. A picture of the Quantum 2000. A full range scan spectrophotometer. One of LT's series/product offerings for online applications.
12. A picture of the PowerScan. A non-moving part system capable of up to 200 full range

AWARD WINNER

scans per second (900-1800 nm). A fiber optic based, multiplexed system (6 measuring points).

13. A description of some of the measuring probe parameters and issues when designing and fabricating.

14. Various types of Transflectance probes.

15. Various probes mounted in a display pipe.

16. A Transflectance probe, with flange, in a pipe.

17. A Transmission pair (probe) mounted in pipe.

18. A retractable Transflectance probe. (Designed to eliminate referencing and cleaning issues)

19. An AR (Absolute Reference) measuring cell. (Designed to eliminate referencing issues.)

20. An instrument used by the State of New Mexico to verify octane in gasoline.

21. An employee at a processing plant collecting a polyol sample for determination of Hydroxyl Number.

22. A Quantum 1200 configured for lab analysis of hydroxyl number in polyols.

23. A DIP probe (Transflectance) measuring a polyol.

24. Textile application. Spools of thread with coatings.

25. A plant QC inspector using a Quantum 1200, with fiber optic assembly, to measure thread surface coatings.

26. The 'face' of fiber optic probe used for measuring surface coating on thread.

27. The LT Carpet Analyzer. Designed and used to identify various carpet fiber type (Nylon 6, Nylon 66, PET, etc...) for recycling purposes. A turn key system, precalibrated.

28. A close-up view of the Carpet Analyzers' probe with single button operation.

29. Indicator lights on the Carpet Analyzer for indicating material type.

30. Sample interface for a polymer melt/extrusion application.

31. Closer view of the polymer melt/extrusion measuring point.

32. An online measuring system utilizing a 'slip-stream' approach.

33. A Quantum 2000 in use a large refinery in the United States. This multiplexed system is currently monitoring eight points from the same system.

34. A close-up view of the Quantum 2000's multiplexing system (Capable of measuring up to 20 points).

35. The multiplexer utilized by the PowerScan series instruments (6 point system).

36. An example of a long fiber optic cable run (this one is for a 250 foot run, in each direction).

37. The measuring points used for the eight point system at the US refinery. These measuring points are all taking advantage of the AR cell.

RHEOLOGICAL BEHAVIOR OF HIGHLY FILLED MATERIALS:

A Case Study

by

Dilhan M. Kalyon

Sept. 20, 1995

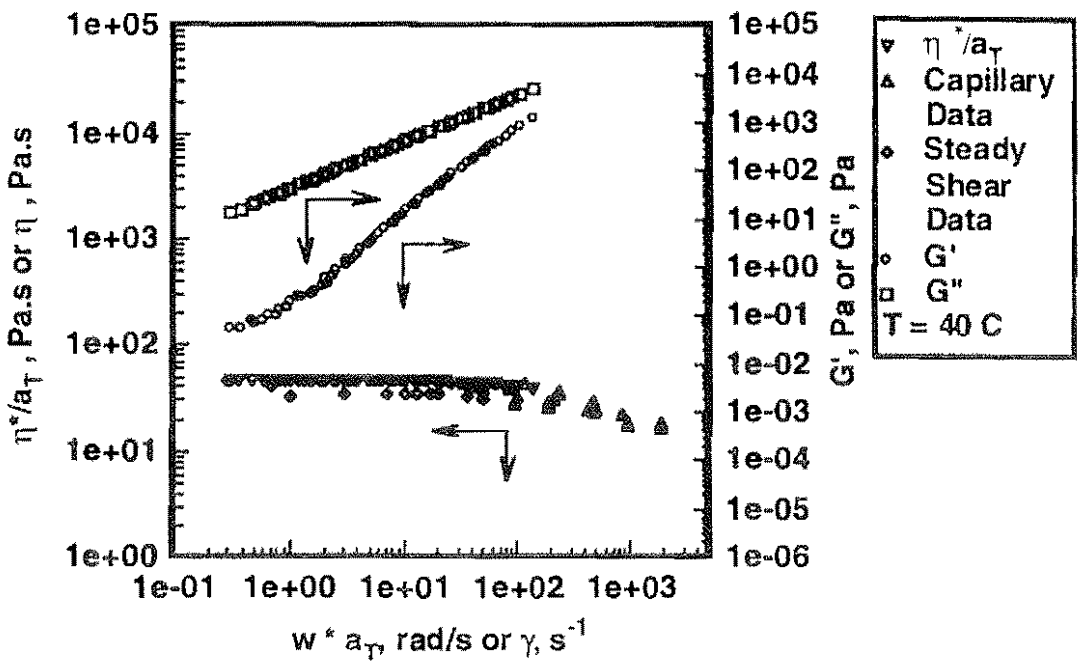
OBJECTIVES

1. To characterize the rheological behavior of a model suspension employing multiple techniques:

- Steady torsional flow
- Small-amplitude oscillatory shear
- Capillary flow
- Rectangular slit flow
- Stress Relaxation data

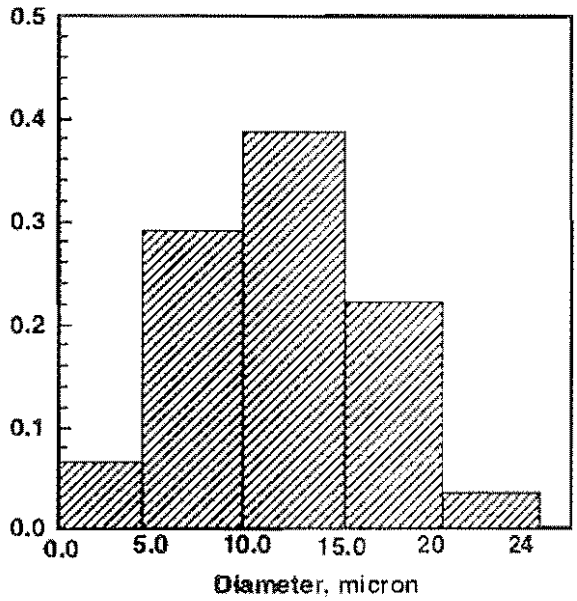
2. To verify the rheological characterization results with actual residence time data collected using tracer based imaging.

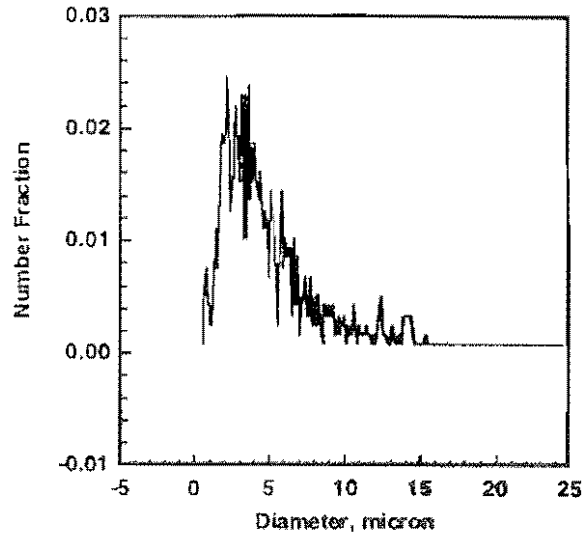
3. To mathematically model the twin screw extrusion process with the collected rheology data and to compare against collected processability data.

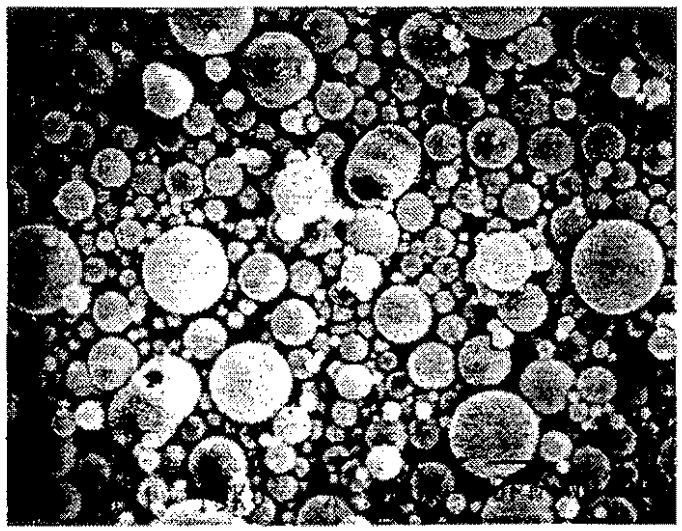


Shear viscosity and linear viscoelastic properties i.e., storage modulus, loss modulus and complex viscosity of binder, silicone 200 (Dow Corning) as a function of shear rate and frequency, respectively.

PY.C2.fig 9







Particle size distribution of hollow glass spheres used in case study.

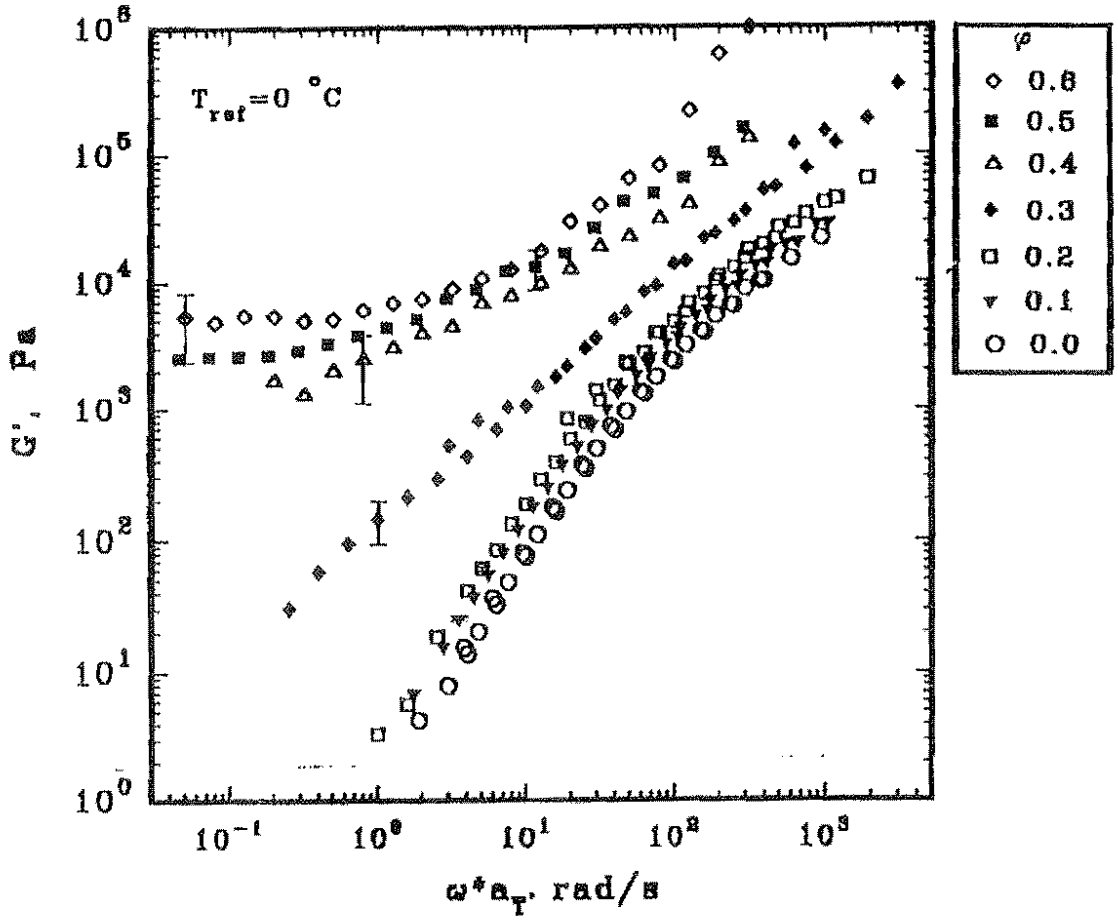


Figure: STORAGE MODULUS VS FREQUENCY
Silicone Oil / Glass Spheres

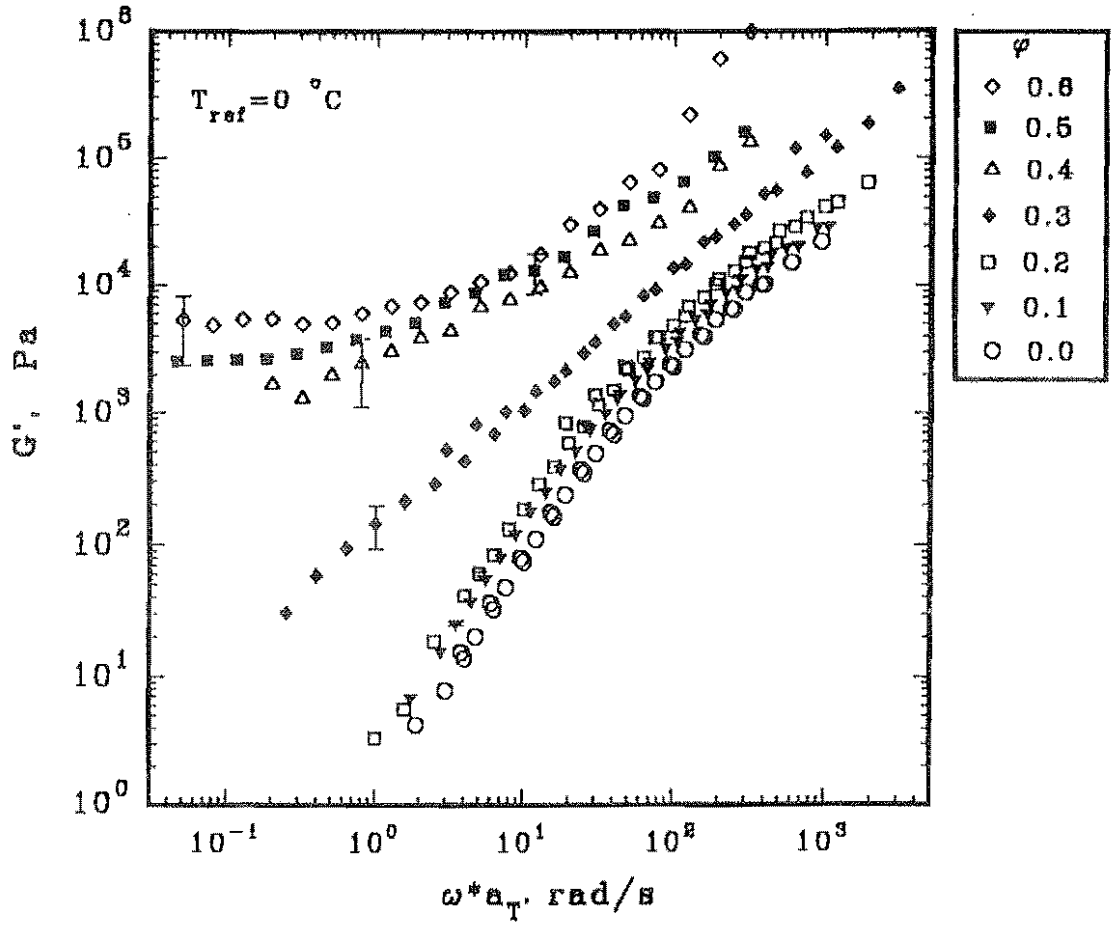


Figure : STORAGE MODULUS VS FREQUENCY
Silicone Oil | Glass Spheres

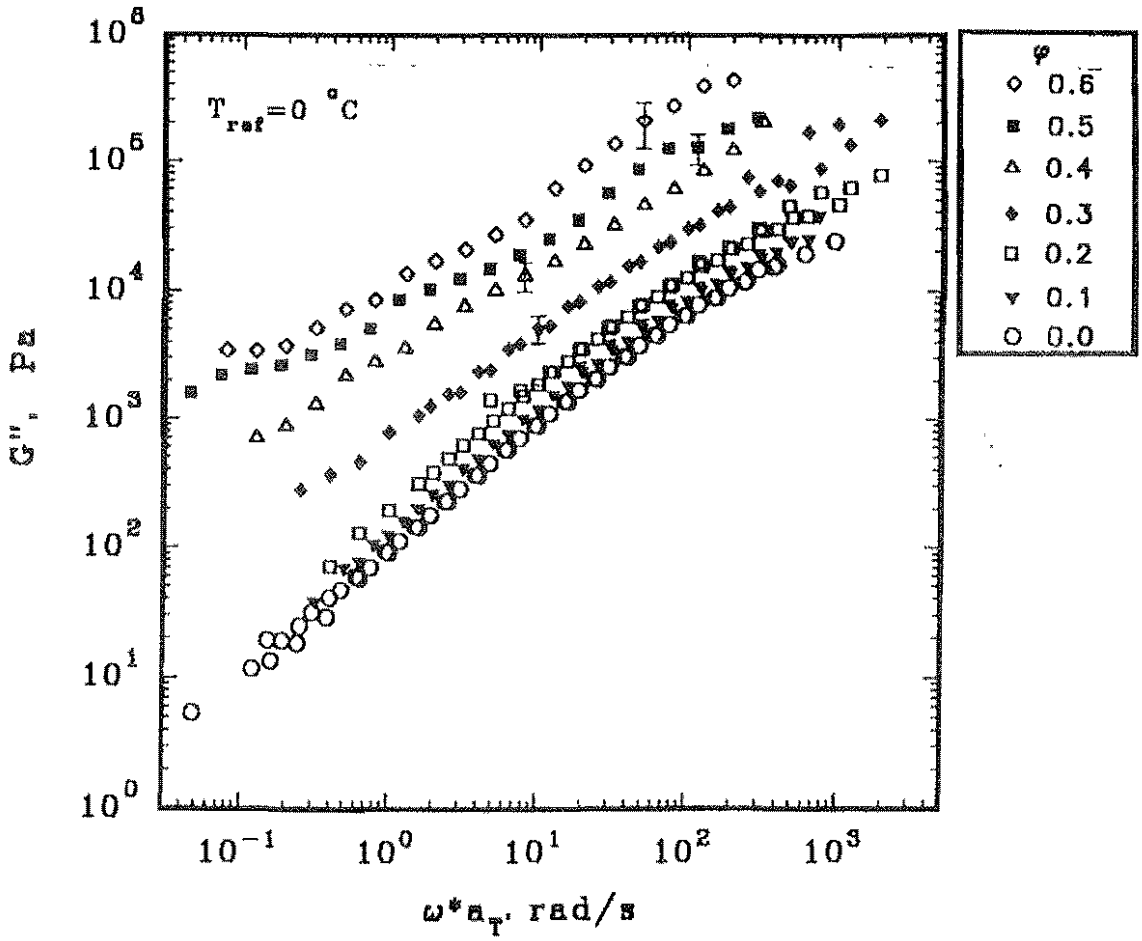
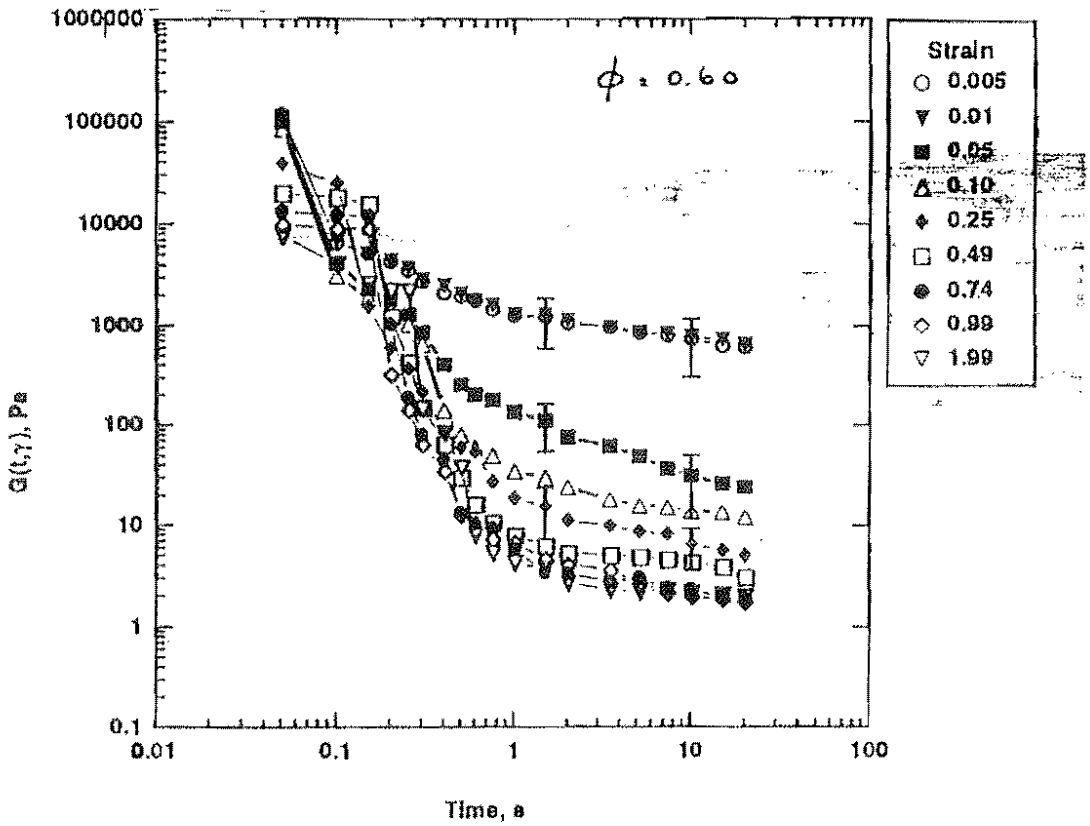
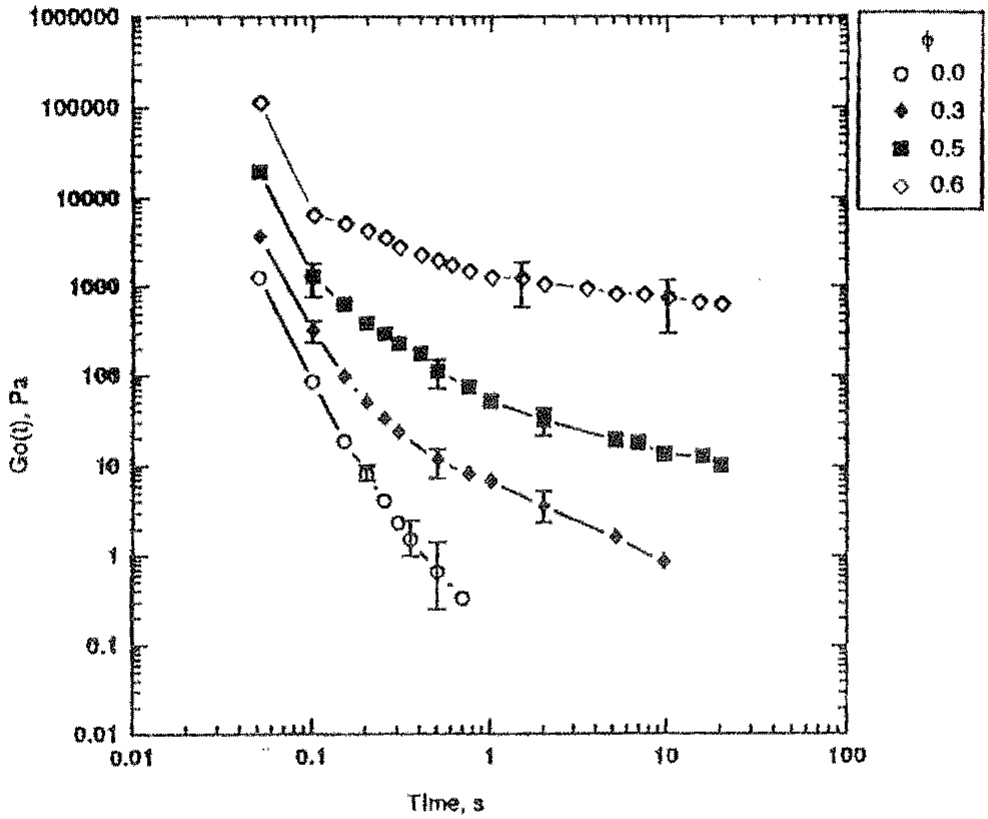


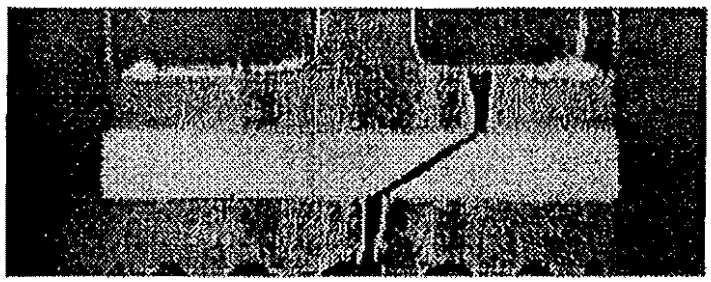
Figure Loss Modulus vs Frequency
Silicone Oil / Glass Spheres

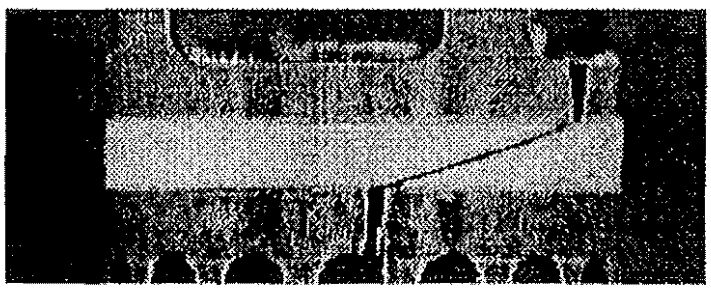


Glass | Silicone 0:2



Combined Go(t)
9/4/05
(experimental values)

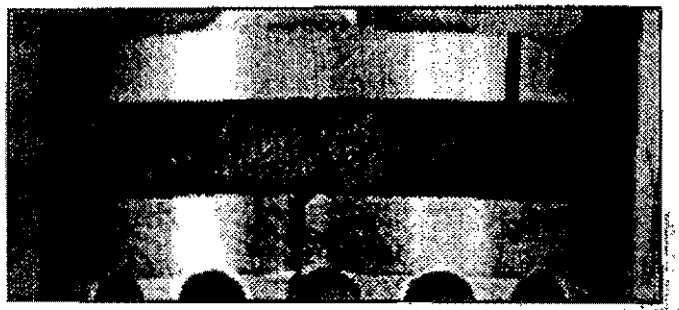


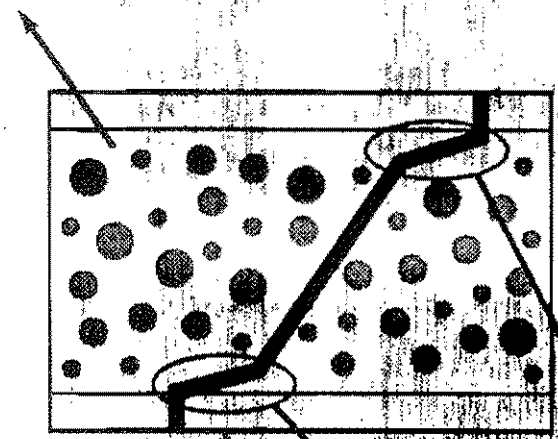


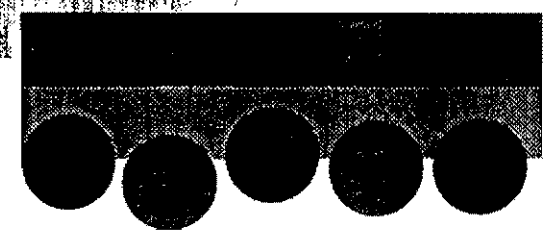
No slip CONDITION AT THE WALL

STEADY TORSIONAL FLOW

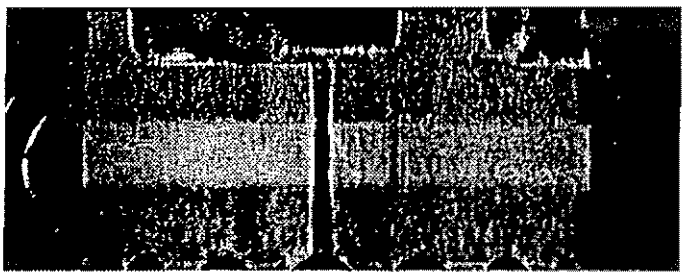
Schematic representation of
" apparent slip" mechanism.



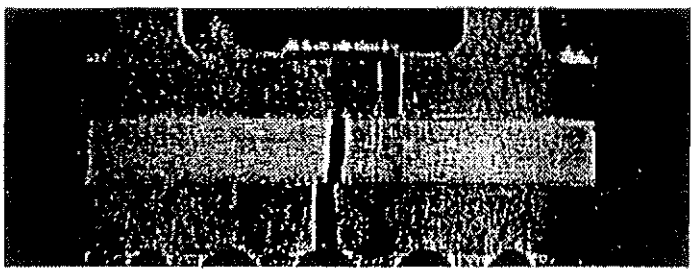




CONCENTRATED SUSPENSIONS EXHIBIT PARTICLE FREE REGIONS NEXT TO SOLID BOUNDARIES WHICH AFFECT THEIR PRESSURIZATION/MIXING DURING PROCESSING



Silicone 200 and Hollow Glass, 60% vol, bef

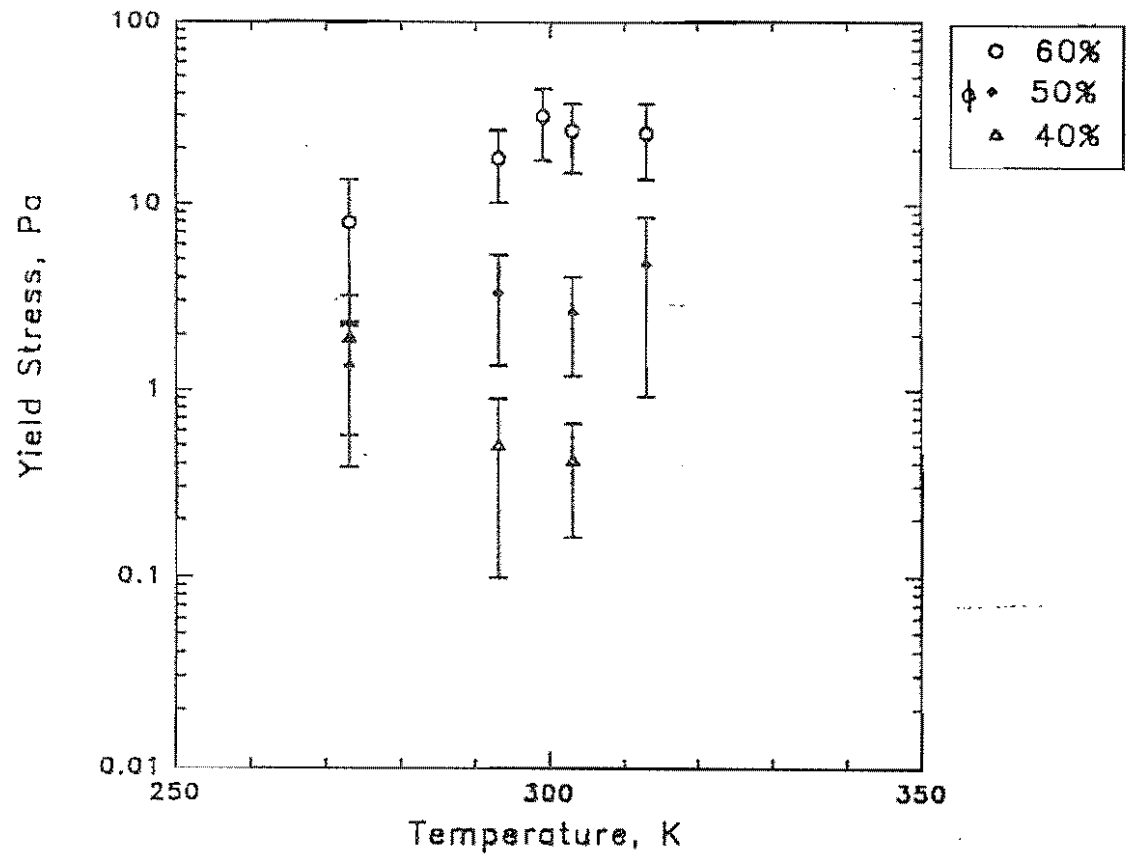


Silicone 200 and Hollow Glass, 60% vol, aft

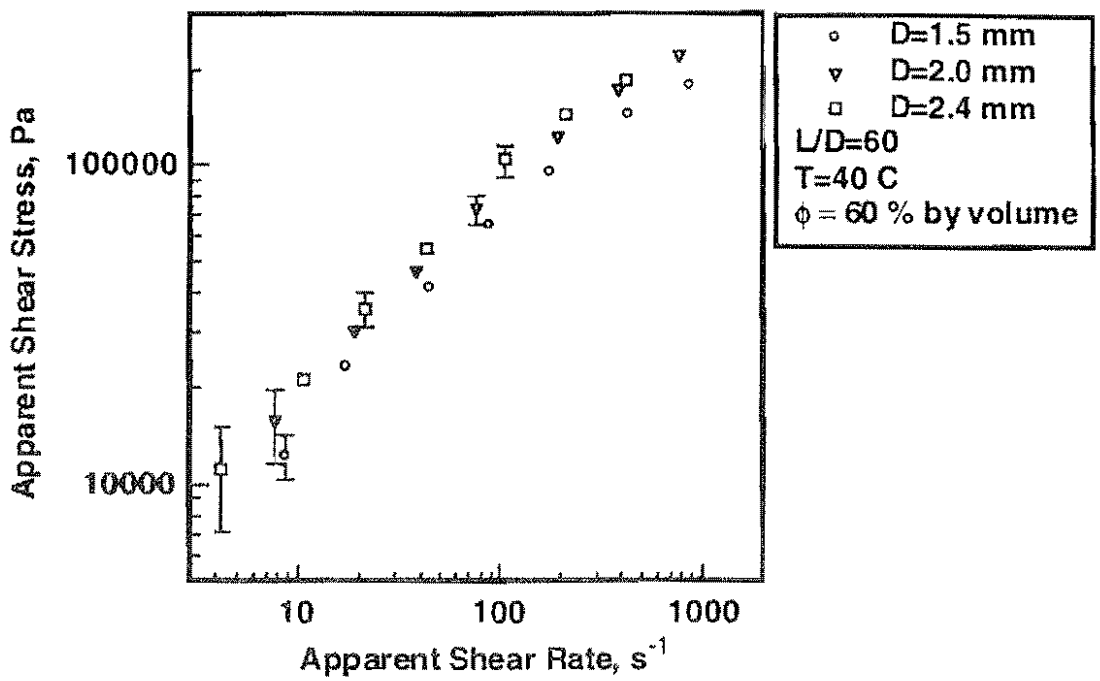
VISCOPLASTICITY & WALL SLIP

WITH $\phi = 0.60$

STEADY TORSIONAL FLOW

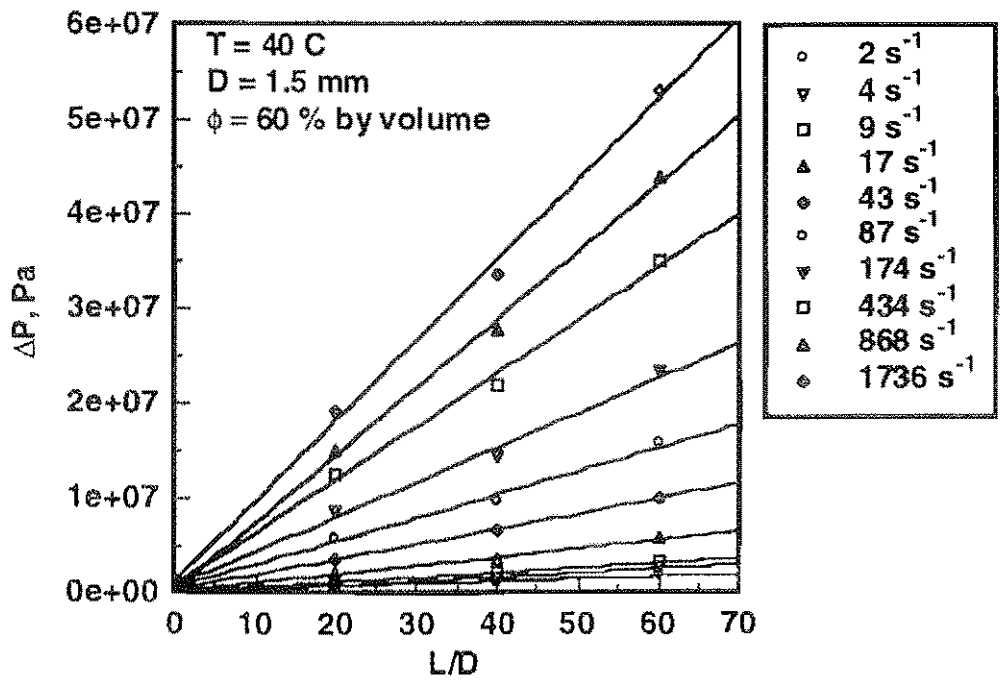


YIELD STRESS AS A FUNCTION OF SOLID LOADING LEVEL, AT VARIOUS TEMPERATURES



Typical apparent shear stress versus apparent shear rate data for the 60 % suspension.

PY.C2.fig 20



Pressure drop versus length over diameter data for the 60 % concentrated suspension.

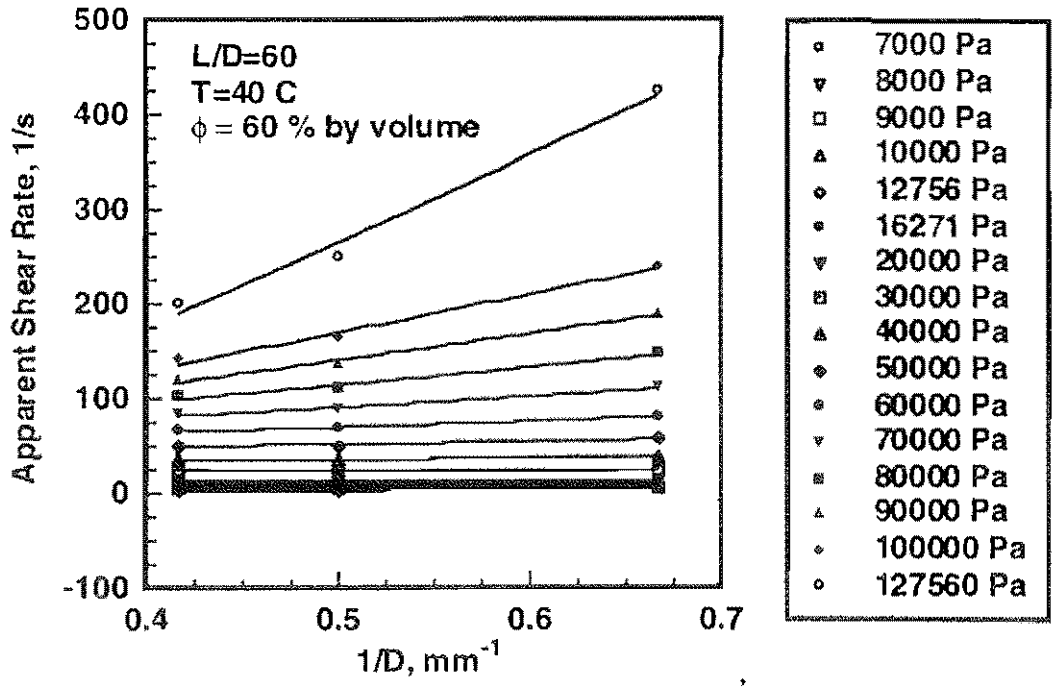
PY.C2.fig 21

Wall Slip and Rabinowitsch Corrections

In the stable capillary flow region the conventional technique of the determination of the slip velocity follows Mooney's analysis. The apparent shear rate at the wall, $\dot{\gamma}_a = 8\ V/D$, is given by (Mooney, 1931):

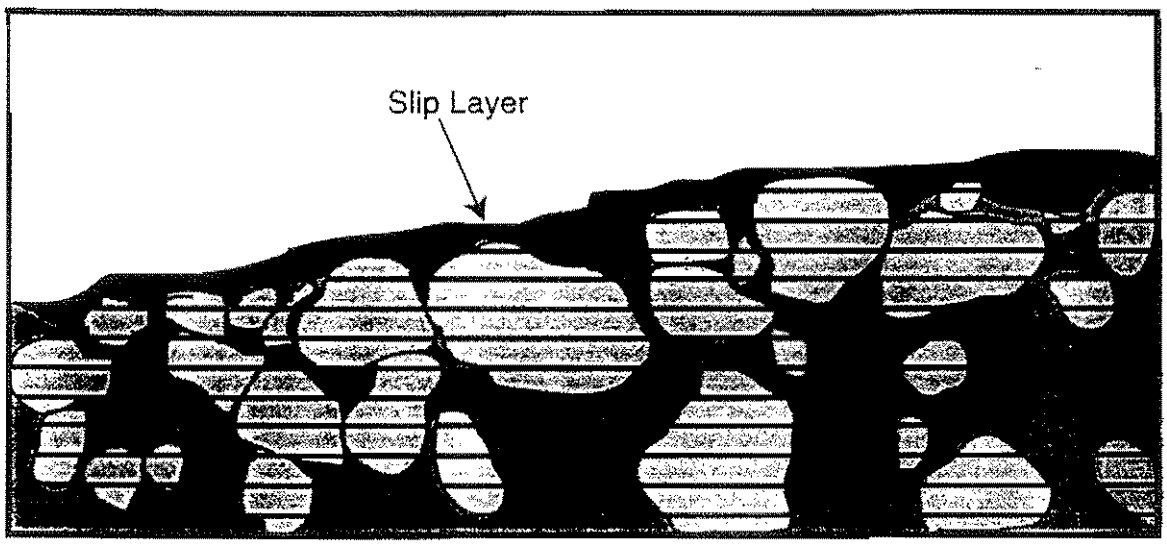
$$\frac{8V}{D} = \frac{4}{\tau_w^3} \int_0^{\tau_w} \tau^2 \dot{\gamma}\, d\tau + \frac{8U_s}{D}$$

- where D is the capillary diameter,
- V is the average velocity of the suspension in the capillary,
- τ is the shear stress,
- τ_w is the shear stress at the wall,
- $\dot{\gamma}$ is the true shear rate, and
- U_s is the slip velocity at the wall.



Apparent shear rate versus the reciprocal of the capillary diameter, 1/D, for different shear stress at the wall values for the 60 % concentrated suspension.

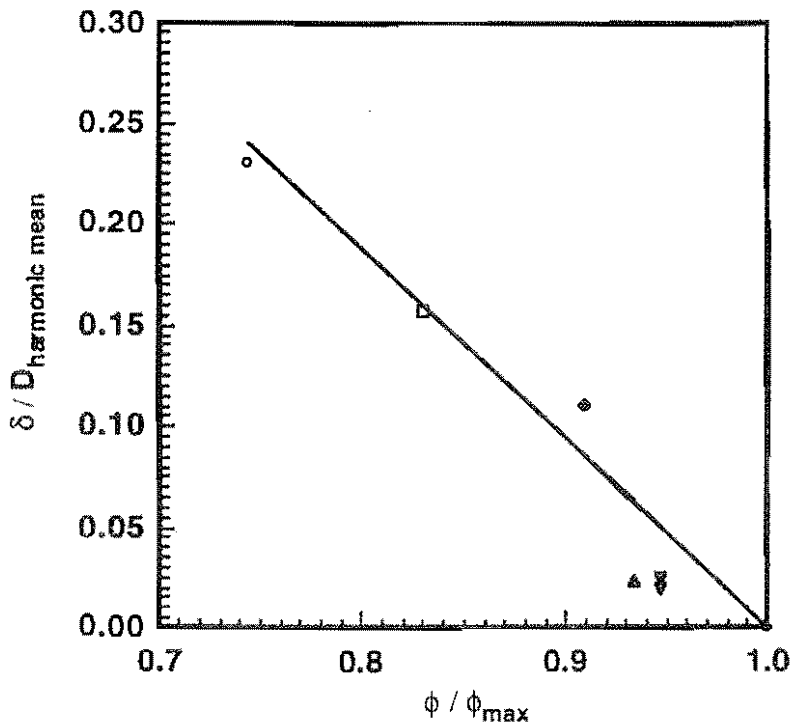
PY.C2.fig 25



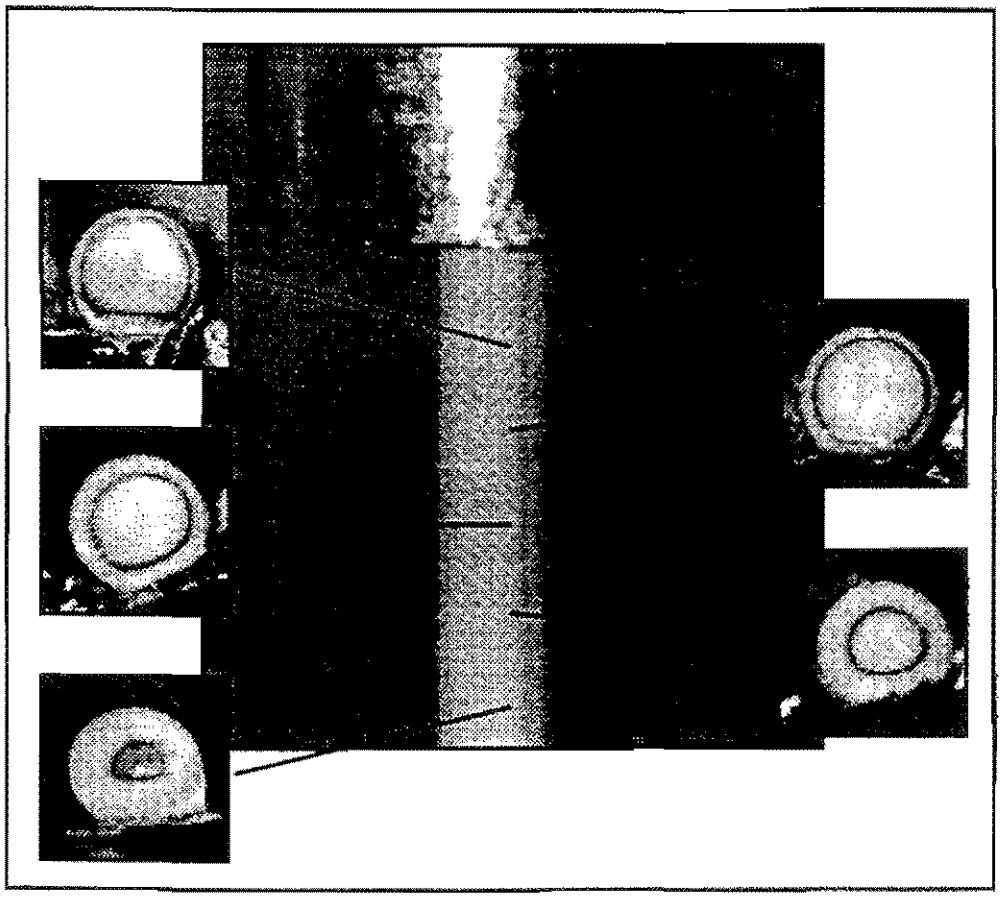
Schematic representation of the formation of the slip layer in capillary flow.

ORDER OF MAGNITUDE ESTIMATE OF WALL SLIP VELOCITY

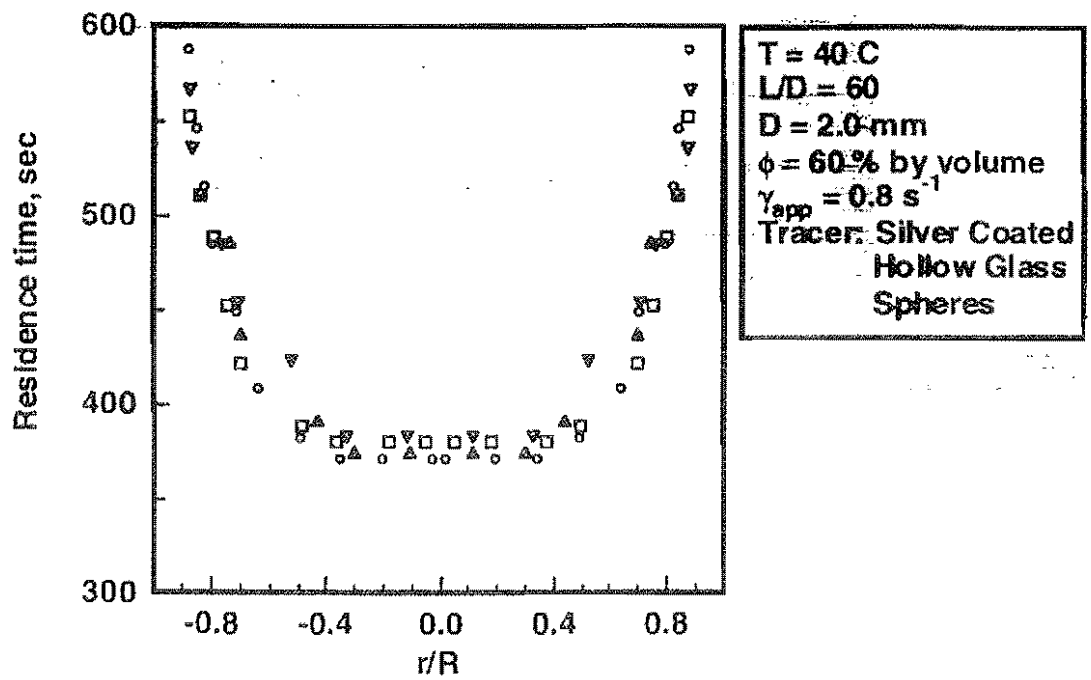
	δ, μm	D_P, μm	ϕ	ϕ_{max}
Suwardie Ph.D. Thesis	0.39	1.7	0.5	0.67
Aral & Kalyon, 1994 (without vacuum)	2.7	106.6	0.63	0.67
Aral & Kalyon 1994 (with vacuum)	2	106.6	0.63	0.67
Kalyon et al., 1993	0.96	40.1	0.77	0.82
Yilmazer & Kalyon 1989	3.4	30.6	0.6	0.66
Kalyon et al., 1995	10.6	68.5	0.64	0.77



Slip layer thickness, δ, over the particle diameter (harmonic mean), Dp, versus the packing fraction, ϕ, over the maximum packing fraction, ϕ_{max}.

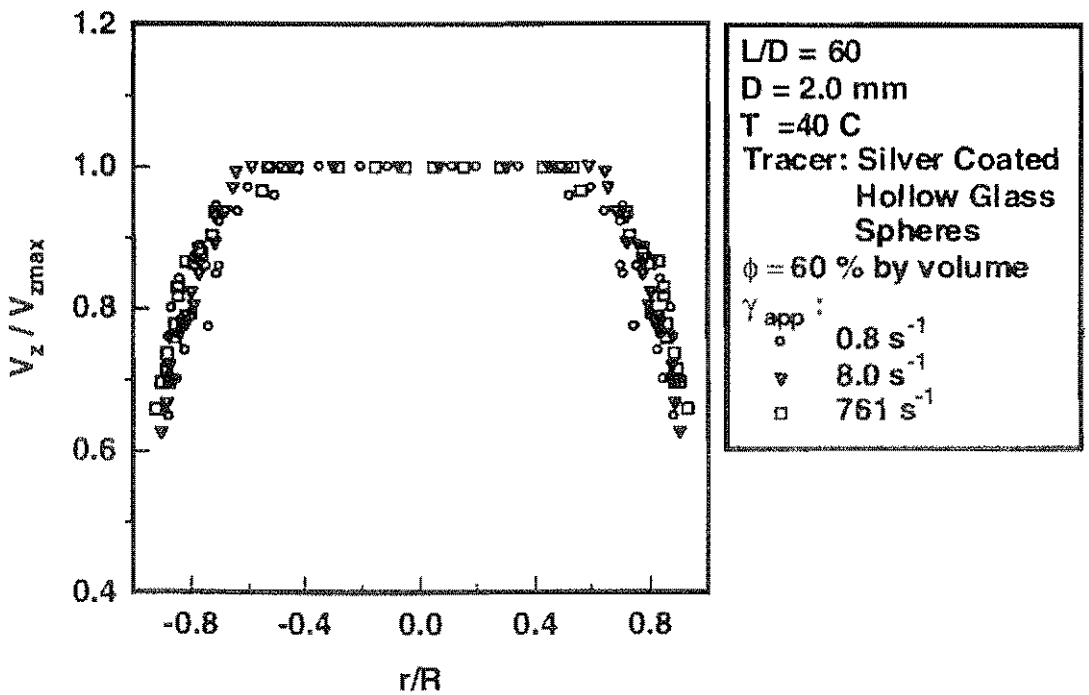


Typical cross-sections of a capillary extrudate incorporated with a tracer involving silver coated glass spheres.



Residence time of the 60 % concentrated suspension in tube flow versus dimensionless radial distance for the apparent shear rates of 0.8 s^{-1}

PY.C2.fig35a



The velocity in the z direction over the maximum velocity in the z direction versus r/R for the apparent shear rates of 0.8, 8.0 and 761 s^{-1}

PY.C2.fig37

- The true shear rate at the wall correcting for both Rabinowitsch and slip effects is found to be (Yilmazer and Kalyon, 1991):

$$\dot{\gamma}_w = \frac{8(Q - Q_s)}{\pi D^3}\left\{3 + \frac{d\ln(Q - Q_s)}{d\ln\tau_w}\right\}$$

where Q is the total volumetric flow rate through the capillary and Q_s is the volumetric flow rate due to slip. Q and Q_s are obtained from:

$$Q = \frac{\pi D^2}{4} V$$

$$Q_s = \frac{\pi D^2}{4} U_s$$

When Q_s becomes equal to Q i.e., U_s is equal to V, the suspension flows only due to slip. In this region of $Q_s/Q = 1$, the flow is thus plug flow.

Rectangular Slit Die Flow

Pressure drop data in slit dies collected as a function of gap height, h, and volumetric flow rate, Q.

- The apparent shear rate values need to be corrected for slip and Rabinowitsch effects using procedures similar to capillary flow.

$$\dot{\gamma}_w = \frac{2(Q - Q_s)}{Wh^2}\left[2 + \frac{d\ln(Q - Q_s)}{d\ln\tau_w}\right]$$

where

- $\dot{\gamma}_w$ is the corrected shear rate at the wall,
- Q_s is the volumetric flow rate due to slip and
- W is the width of the slit die, 0.06 m.

Let us now analyze plane Couette flow (representation of the viscometric steady torsional flow, where the fluid is sandwiched in between two infinitely long parallel plates, with the top wall moving at velocity, $\overline{V}_w$, in the z-direction and bottom stationary), for the fully-developed flow equations subject to Navier's wall slip condition:

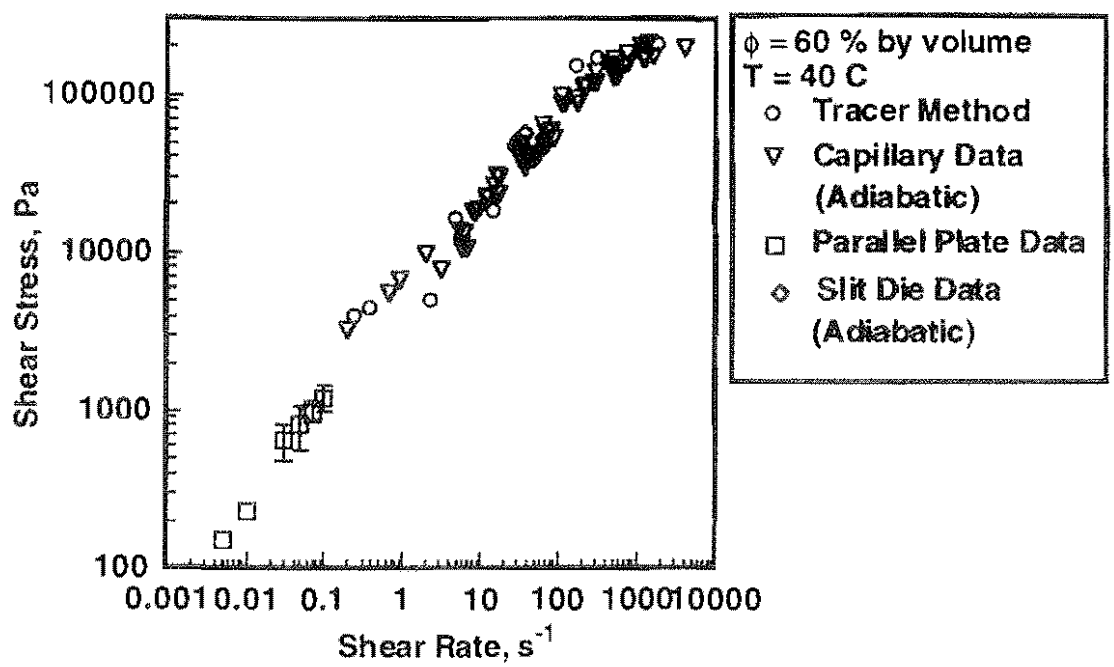
$$\vec{t}\cdot\left(\vec{V}_z-\vec{V}_w\right)=\beta\left(\vec{n}\vec{t}:\underline{\underline{\tau}}\right)$$

- $\vec{t}$ and $\vec{n}$ represent the unit tangential and normal vectors, respectively, $\vec{V}_z$ is the velocity of the fluid at the wall and $\vec{V}_w$ is the velocity of the wall.

- The velocity distribution V_z (y) in pure drag flow occurring in plane Couette flow becomes:

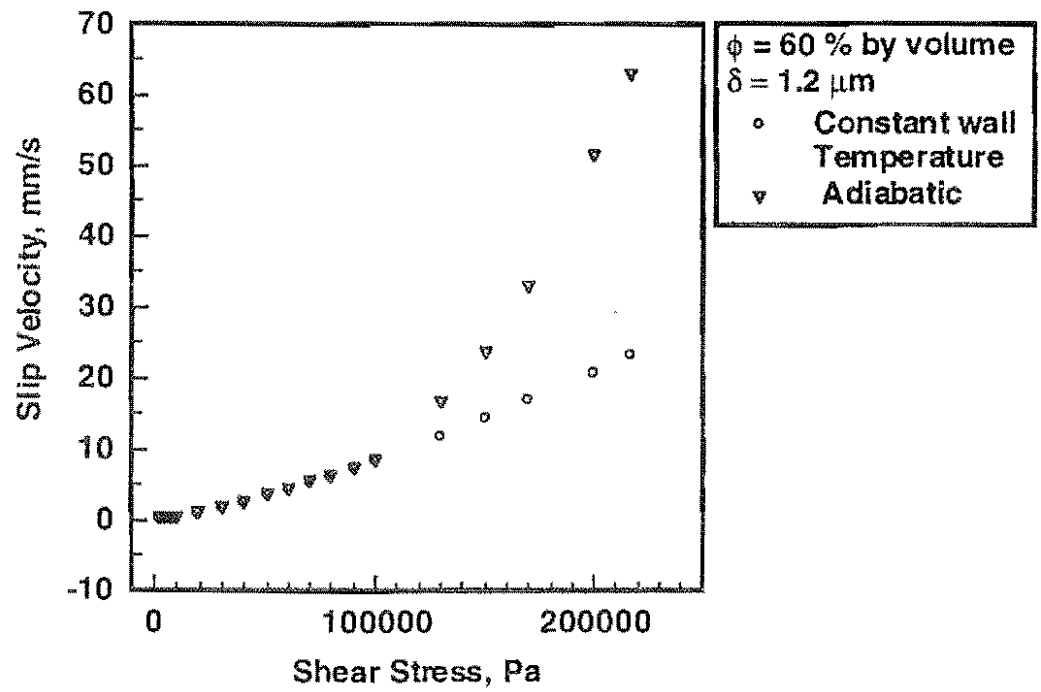
$$V_z=\frac{\left(\overline{V_w}+2\beta\tau_{zy}\right)}{H}y-\beta\tau_{zy}$$

where τ_{zy} is the shear stress which is constant over the cross-sectional area transverse to flow direction at any radial location and H is the gap between the two plates.

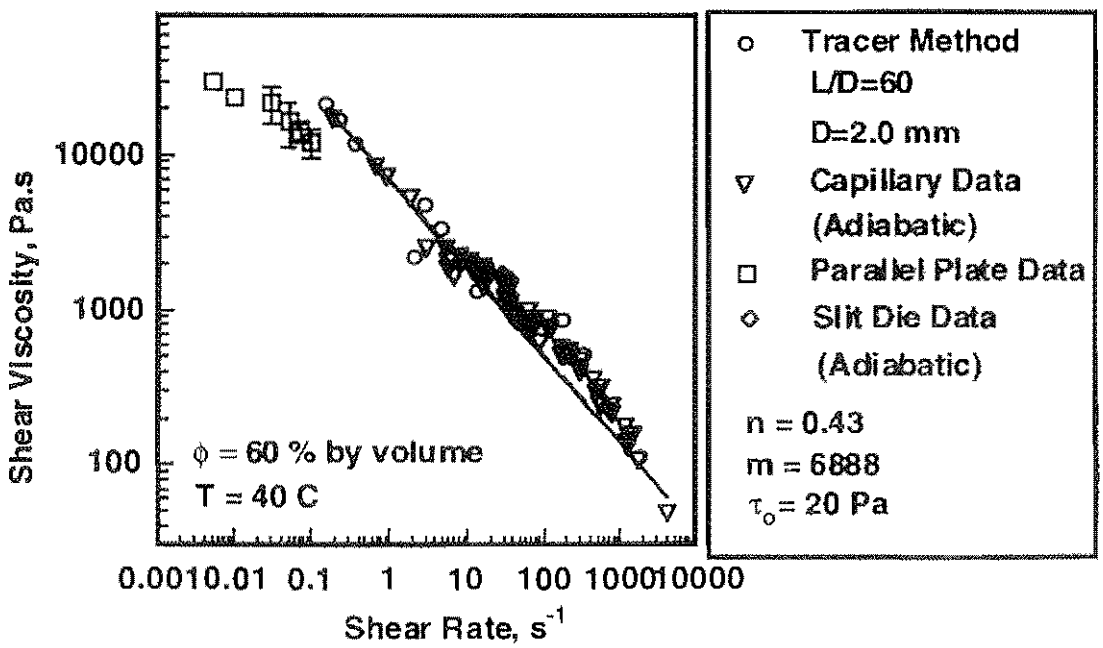


Shear stress at the wall versus true shear rate behavior of the 60 % concentrated suspension obtained from tracer analysis in tube flow, capillary flow, rectangular slit die flow and parallel plate torsional flow.

PY.C2.fig38



Slip velocity versus shear stress behavior of the 60 % concentrated suspension assuming constant wall temperature of 40 C or adiabatic wall condition.



Shear viscosity versus true shear rate behavior of the 60 % concentrated suspension obtained from tracer analysis in tube flow, capillary flow, rectangular slit die flow and parallel plate torsional flow.

TWIN SCREW EXTRUSION PROCESSING OF HIGHLY FILLED MATERIALS: EXPERIMENTS VS. THEORY

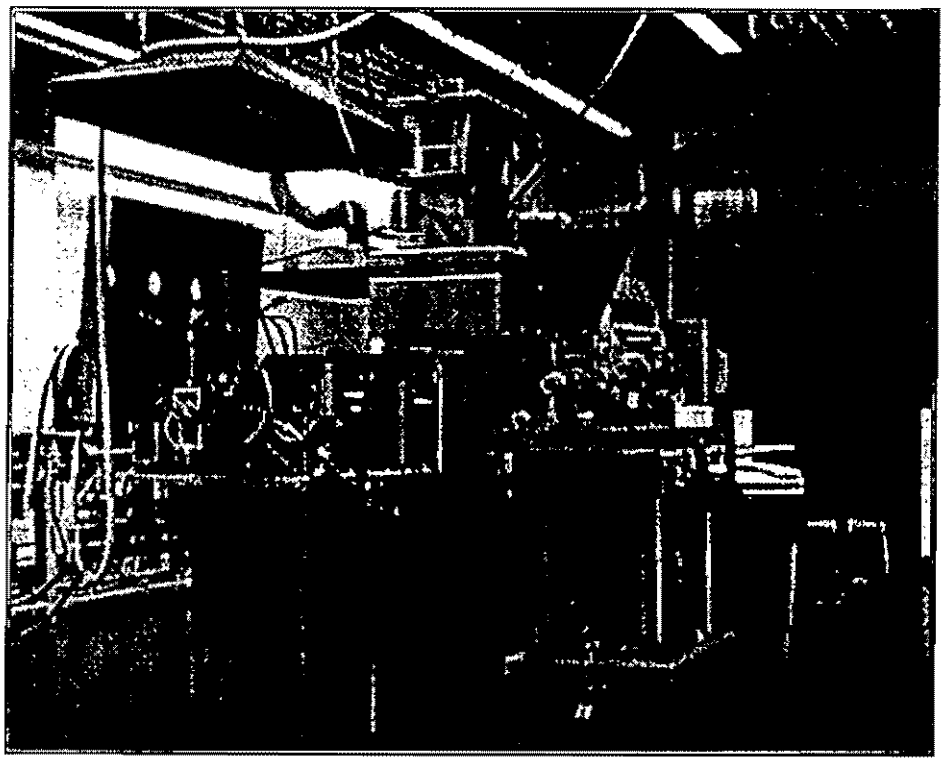
by

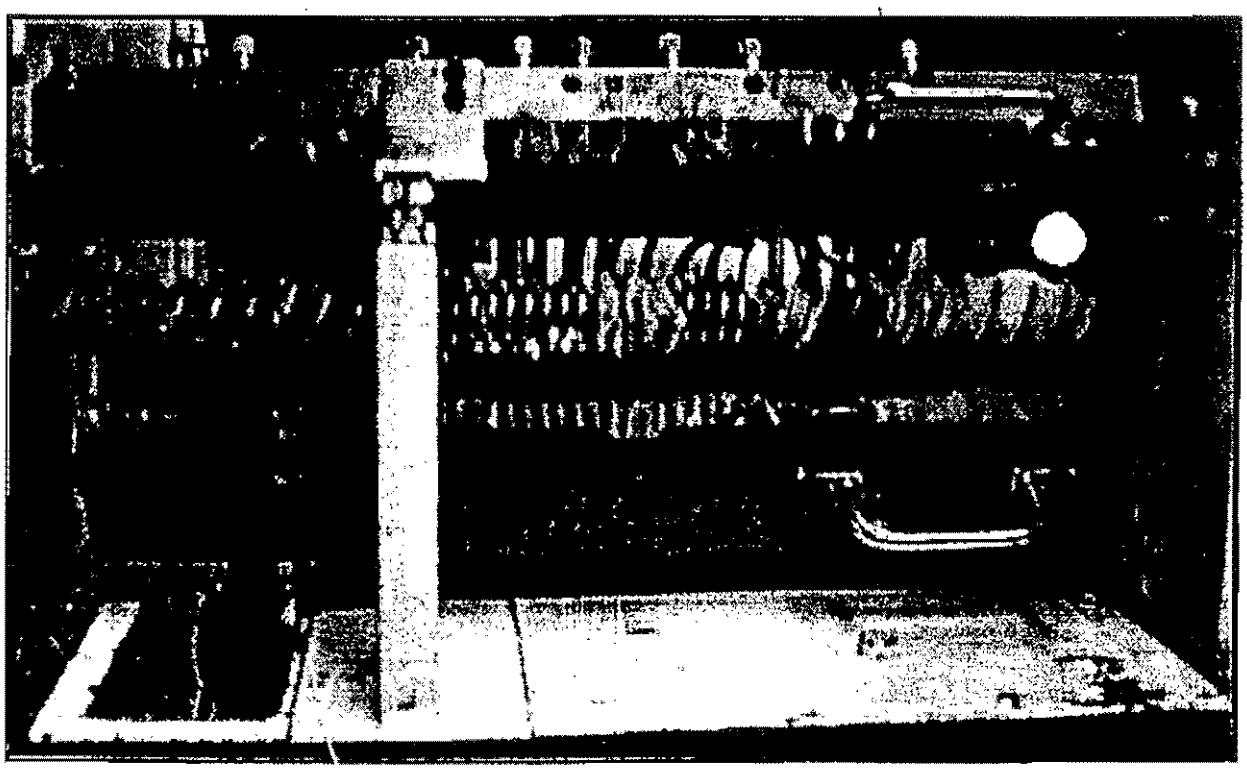
Dilhan M. Kalyon

OBJECTIVES

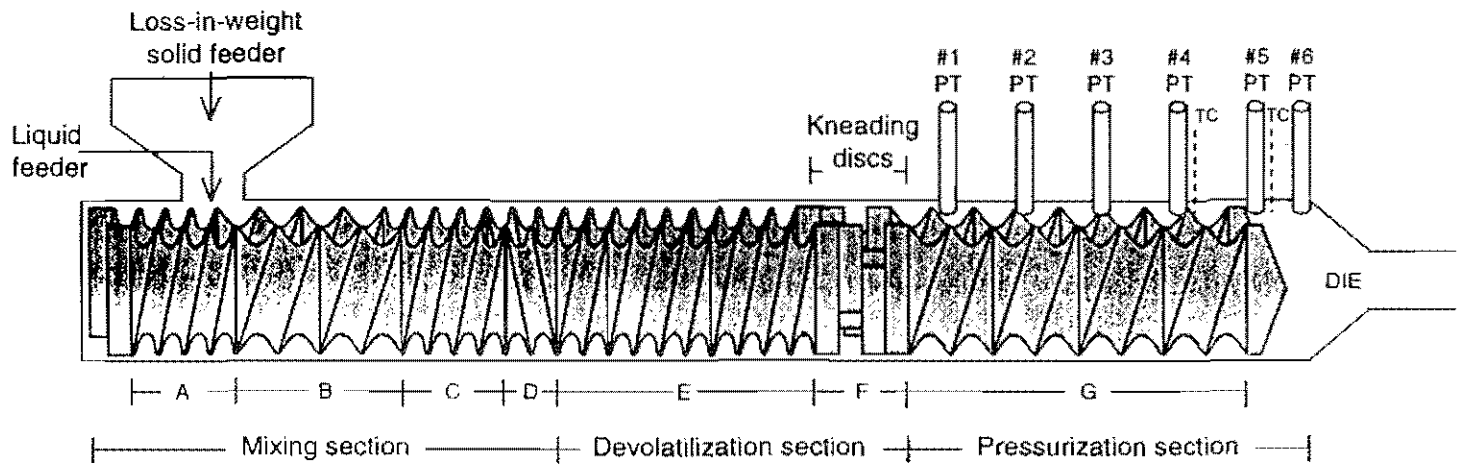
1. To collect experimental data from an industrial-size and well-instrumented twin screw extrusion line.

2. To mathematically model the thermo-mechanical history in the extrusion process and to compare the simulation results with the experimental findings.





APV 50.8 mm Clam Shell Twin Screw Extruder at HFMI's processing laboratory and the twin screws shown with barrel split open.



Screw configuration of the twin screw extruder used in this study.

	Mean	Standard Deviation	95% Confidence
Intervals			
Batch Mixed	60.0	1.397	3.464
First TSE run	60.6	0.346	0.859
Second TSE run	60.9	0.216	0.344
Beginning	60.8	0.071	0.602
End	61.1	0.212	1.805
First and Second TSE runs	60.8	0.298	0.276

Penalty Method for Pressure:

$$p = \beta_p \eta \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right)$$

X-Momentum Equation:

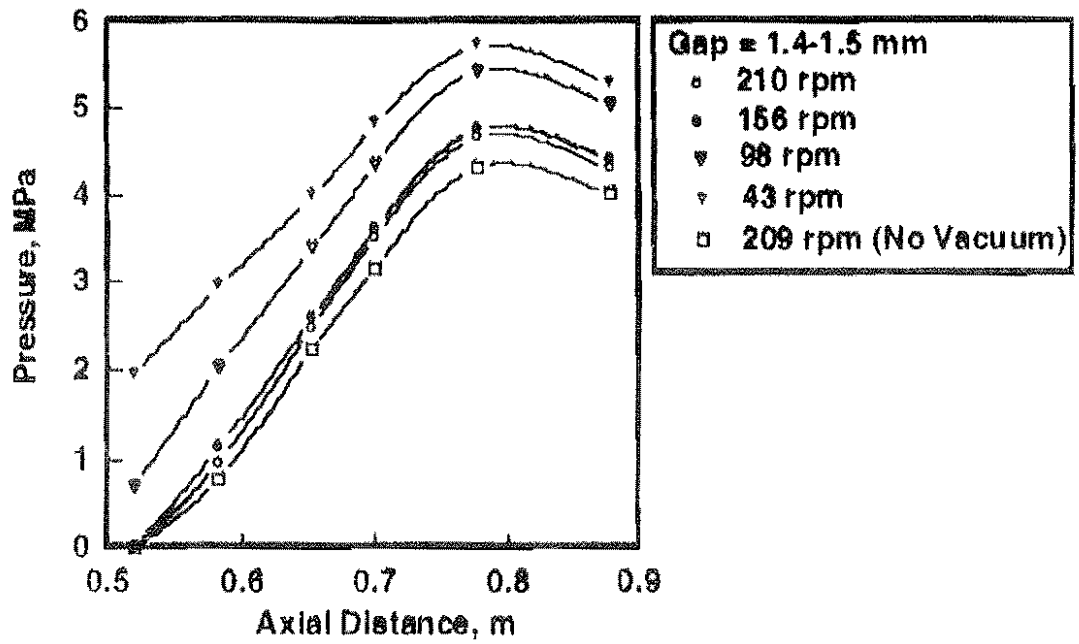
$$\frac{\partial}{\partial x}\left[\beta_p \eta \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right)\right] - \frac{\partial}{\partial x}\left(2\eta \frac{\partial v_x}{\partial x} \right) - \frac{\partial}{\partial y}\left[\eta \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)\right] - \frac{\partial}{\partial z}\left[\eta \left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right)\right] = 0$$

Y-Momentum Equation:

$$\frac{\partial}{\partial y}\left[\beta_p \eta \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right)\right] - \frac{\partial}{\partial x}\left[\eta \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)\right] - \frac{\partial}{\partial y}\left(2\eta \frac{\partial v_y}{\partial y} \right) - \frac{\partial}{\partial z}\left[\eta \left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \right)\right] = 0$$

Z-Momentum Equation:

$$\frac{\partial}{\partial z}\left[\beta_p \eta \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right)\right] - \frac{\partial}{\partial x}\left[\eta \left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right)\right] - \frac{\partial}{\partial y}\left[\eta \left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \right)\right] - \frac{\partial}{\partial z}\left(2\eta \frac{\partial v_z}{\partial z} \right) = 0$$



Effect of screw speed on the pressure profiles in a twin screw extruder.

PY.C2.fig42

$$Pe\left(u_x\frac{\partial\theta}{\partial x}+u_y\frac{\partial\theta}{\partial y}+u_z\frac{\partial\theta}{\partial z}\right)=\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}\right)+G\eta^*\left(|\dot{\gamma}|^*\right)^2$$

$$\int_z^{z+\Delta z}\left\{\int_D\left[\ \overline{w}^f Pe\left(u_x\frac{\partial\theta}{\partial x}+u_y\frac{\partial\theta}{\partial y}+u_z\frac{\partial\theta}{\partial z}\right)+\nabla\overline{w}^f\cdot\nabla\theta-\overline{w}^f G\left(|\dot{\gamma}|^*\right)^2\eta^*\ \right]dD-\int_{\Gamma_s}\overline{w}^f(\nabla\theta\cdot n)d\Gamma_s\right\}dz=0$$

at $z = 0, \theta = 0$

on barrel surface $\theta = 1$

on screw surface $\partial\theta / \partial n = 0$

$$\tau_{yz} = -m\left|\frac{dv_z}{dy}\right|^{n-1}\frac{dv_z}{dy} \pm \tau_o \qquad \left|\tau_{yz}\right| \geq \tau_o$$

$$\frac{dv_z}{dy} = 0 \qquad \left|\tau_{yz}\right| \leq \tau_o$$

$$\underline{t}\cdot(\underline{v} - \underline{v}_{solid}) = \beta \underline{n}\underline{t} : \underline{\underline{\pi}}$$

$$u_{st} = (\beta_t / v_w)\tau_{yz}(H)$$

$$u_{sb} = -(\beta_b / v_w)\tau_{yz}(0)$$

PECLET NO:

$$Pe = \rho C_p \omega R_s^2 / k$$

GRIFFITH NO:

$$G = m_o \omega^{n-1} (\omega R_s)^2 / k (T_b - T_o)$$

Wall Slip Condition

$$\vec{t}\cdot(\vec{u}-\vec{u}_b) = \beta(\vec{n}\vec{t}:\underset{\approx}{\pi})$$

No Material Exchange

$$\vec{n}\cdot(\vec{u}-\vec{u}_b) = 0$$

$$\vec{n}\vec{t}:\underset{\approx}{\pi} = \frac{\vec{t}\cdot(\vec{U}-\vec{U}_b)}{\beta}$$

β : slip parameter

$$\text{As } \lambda_s \longrightarrow 0$$

$$\vec{n}\cdot(\vec{U}-\vec{U}_b)=0$$

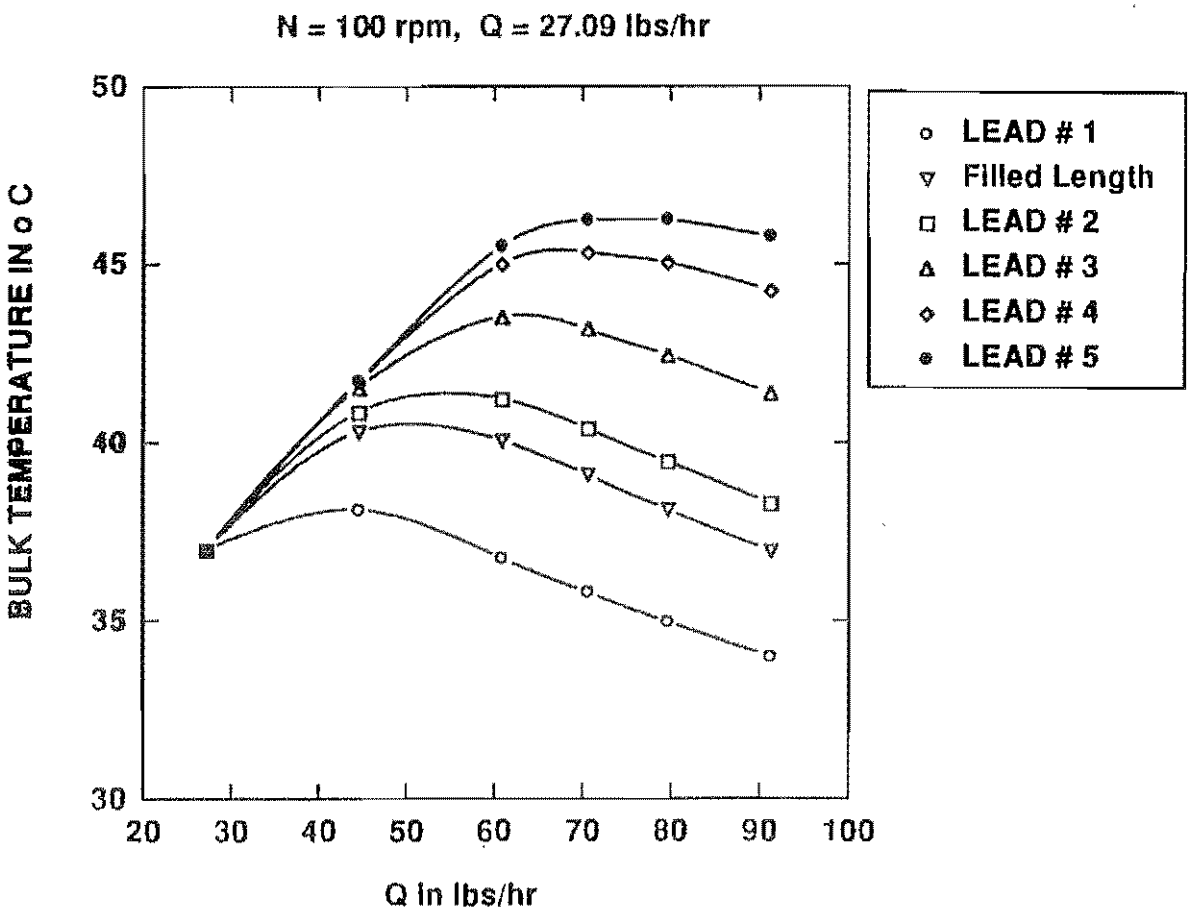
$$\vec{n}\vec{n}:\underset{\approx}{\pi} = \frac{\vec{n}\cdot(\vec{U}-\vec{U}_b)}{\lambda_s}$$

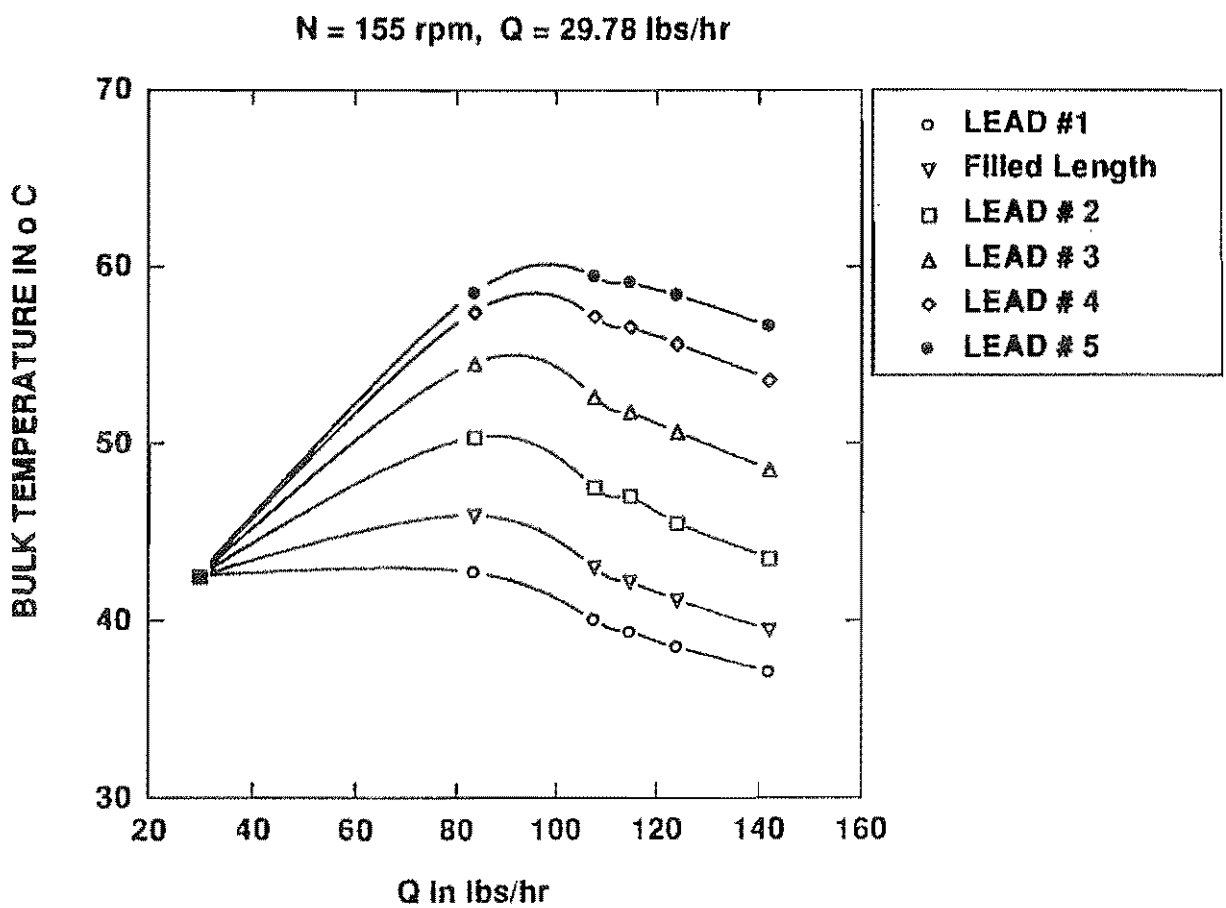
λ_s : penalty parameter for slip

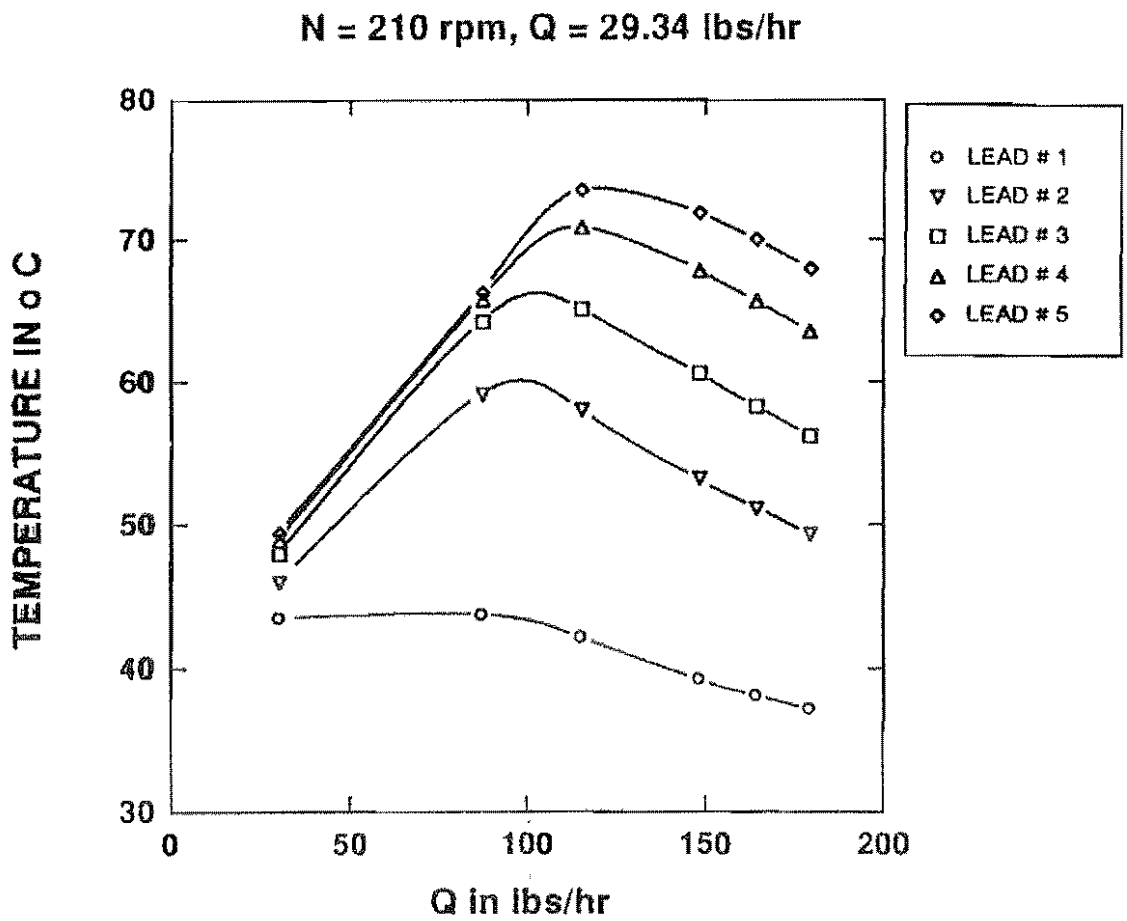
Implementation of Wall Slip

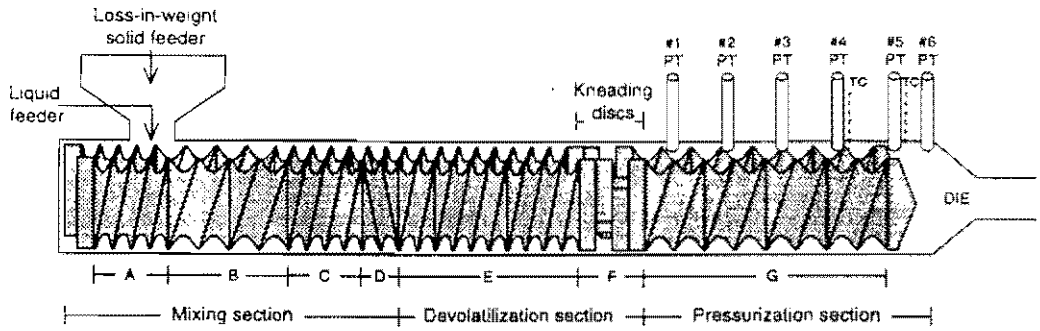
$$\int_D (\nabla w^f \cdot \underset{\approx}{\pi})\, dD - \int_{\Gamma_s} w^f (\vec{n}\vec{t} : \underset{\approx}{\pi})\, \vec{t}\, d\Gamma_s$$

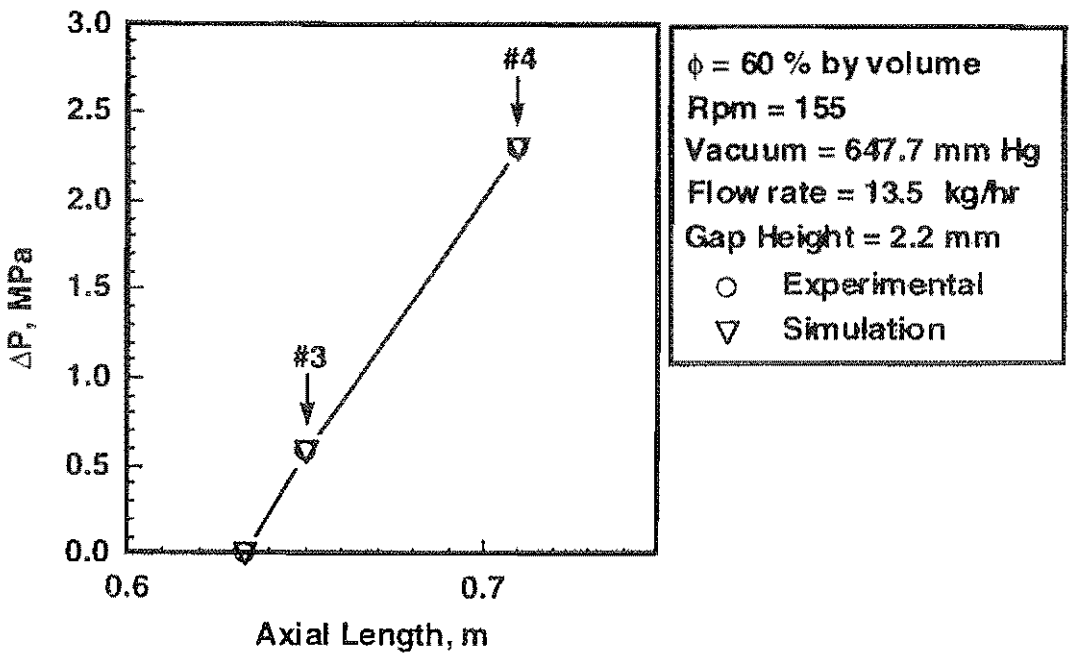
$$- \int_{\Gamma_s} w^f (\vec{n}\vec{n} : \underset{\approx}{\pi})\, \vec{n}\, d\Gamma_s = 0$$

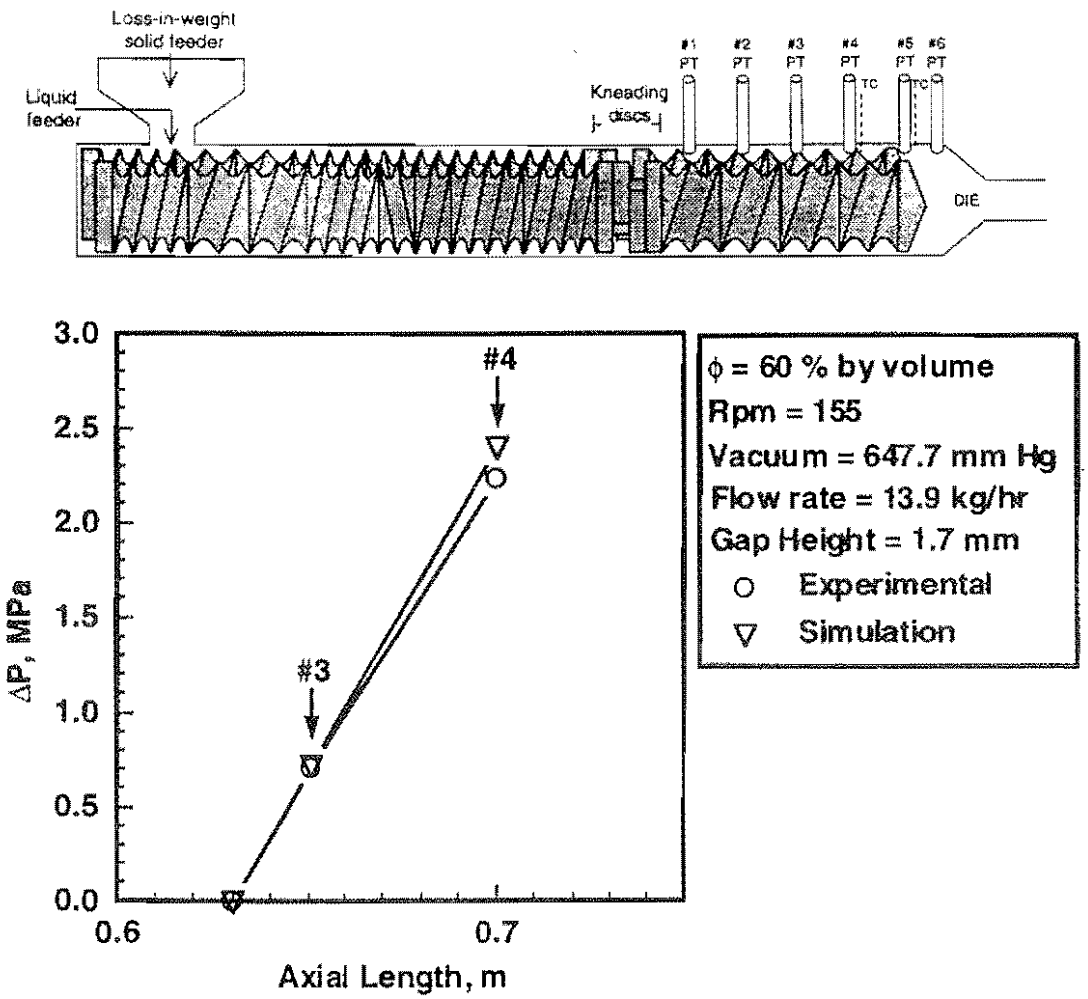

N = 100 rpm, Q = 27.09 lbs/hr
BULK TEMPERATURE IN o C
Q in lbs/hr
50
45
40
35
30
20
30
40
50
60
70
80
90
100
LEAD # 1
Filled Length
LEAD # 2
LEAD # 3
LEAD # 4
LEAD # 5


N = 155 rpm, Q = 29.78 lbs/hr
BULK TEMPERATURE IN o C
70
60
50
40
30
20
40
60
80
100
120
140
160
Q in lbs/hr
LEAD #1
Filled Length
LEAD # 2
LEAD # 3
LEAD # 4
LEAD # 5

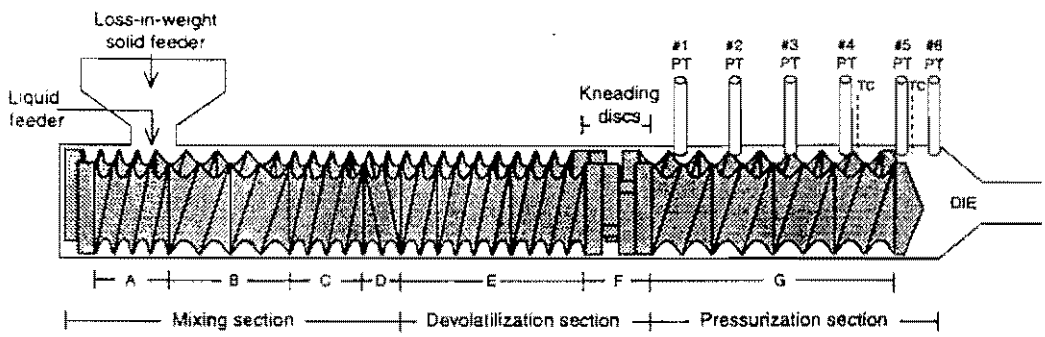

N = 210 rpm, Q = 29.34 lbs/hr
TEMPERATURE IN o C
Q in lbs/hr
80
70
60
50
40
30
0
50
100
150
200
LEAD # 1
LEAD # 2
LEAD # 3
LEAD # 4
LEAD # 5

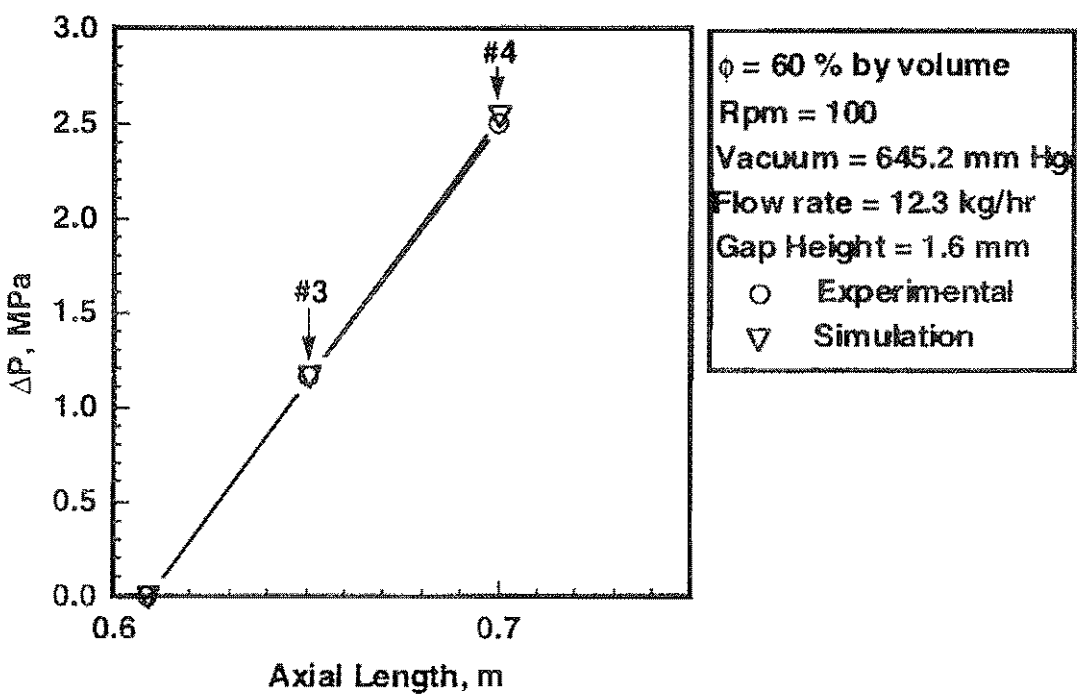

Loss-in-weight solid feeder
Liquid feeder
Kneading discs
#1 PT
#2 PT
#3 PT
#4 PT
#5 PT
#6 PT
TC
TC
DIE
A
B
C
D
E
F
G
Mixing section
Devolatilization section
Pressurization section


3.0
2.5
2.0
1.5
1.0
0.5
0.0
ΔP, MPa
0.6
0.7
Axial Length, m
#4
#3
ϕ = 60 % by volume
Rpm = 155
Vacuum = 647.7 mm Hg
Flow rate = 13.5 kg/hr
Gap Height = 2.2 mm
Experimental
Simulation

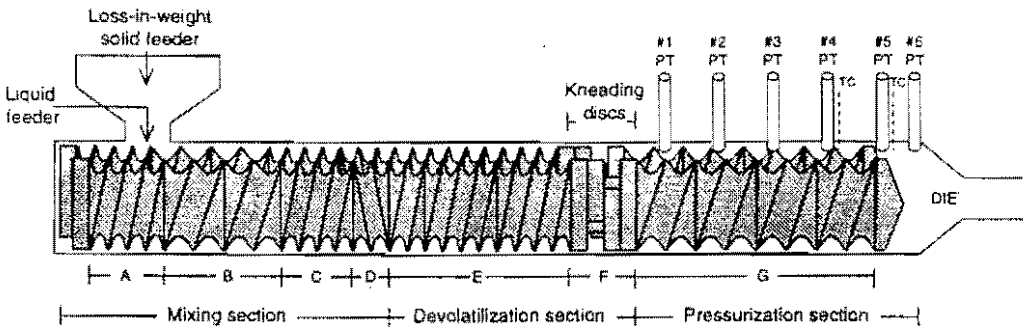


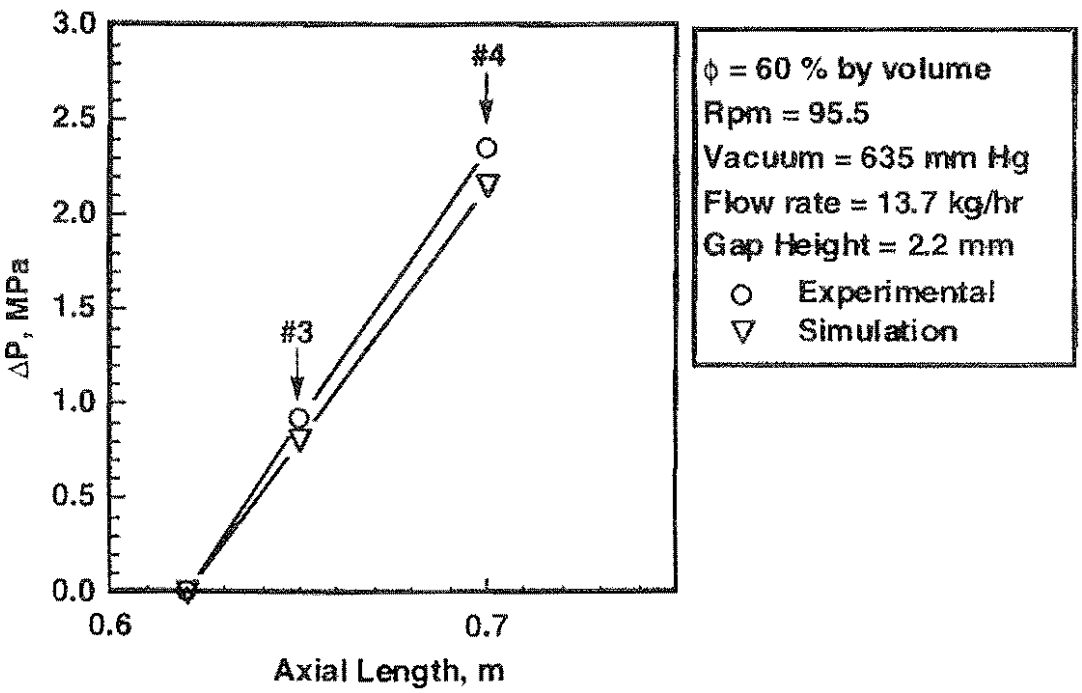
Pressure versus axial distance in a twin screw extruder obtained experimentally and from the Finite Element Method based mathematical modeling. The screw speed and the volumetric flow rate were 155 rpm and 13.9 kg/hr, respectively.



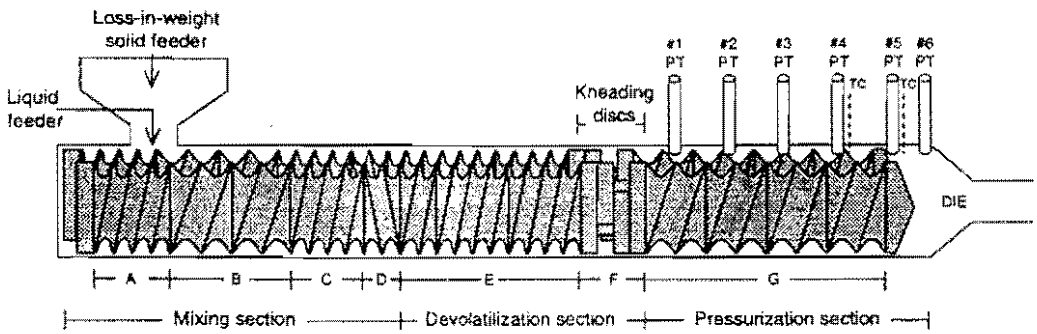


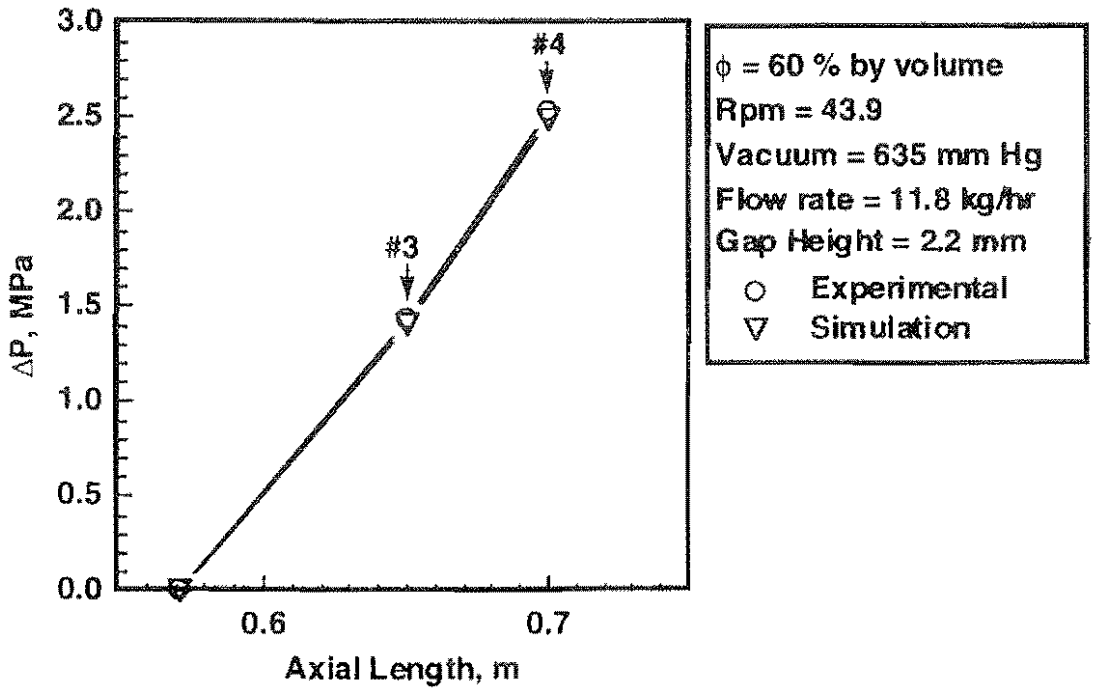
Pressure versus axial distance in a twin screw extruder obtained experimentally and from the Finite Element Method based mathematical modeling. The screw speed and the volumetric flow rate were 100 rpm and 12.3 kg/hr, respectively.



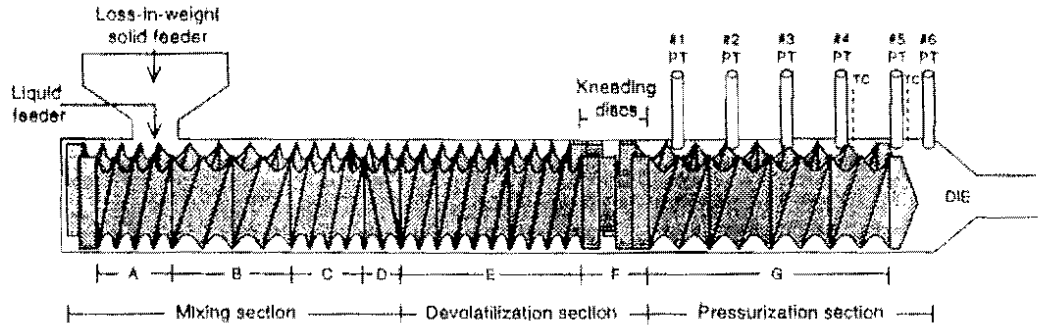


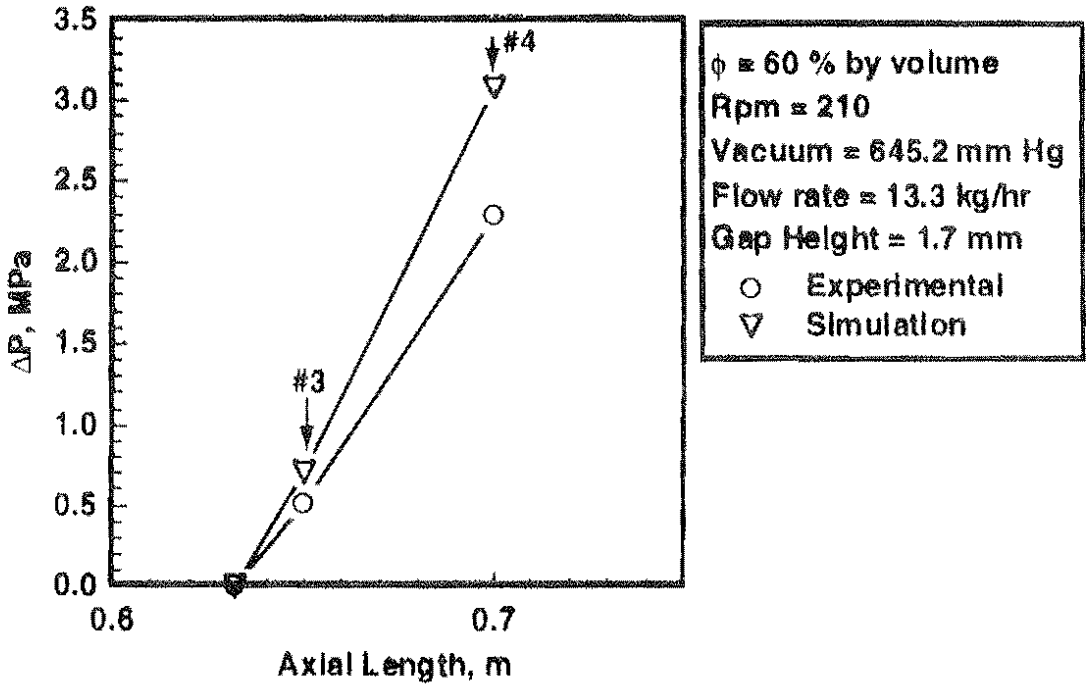
Pressure versus axial distance in a twin screw extruder obtained experimentally and from the Finite Element Method based mathematical modeling. The screw speed and the volumetric flow rate were 95.5 rpm and 13.7 kg/hr, respectively.





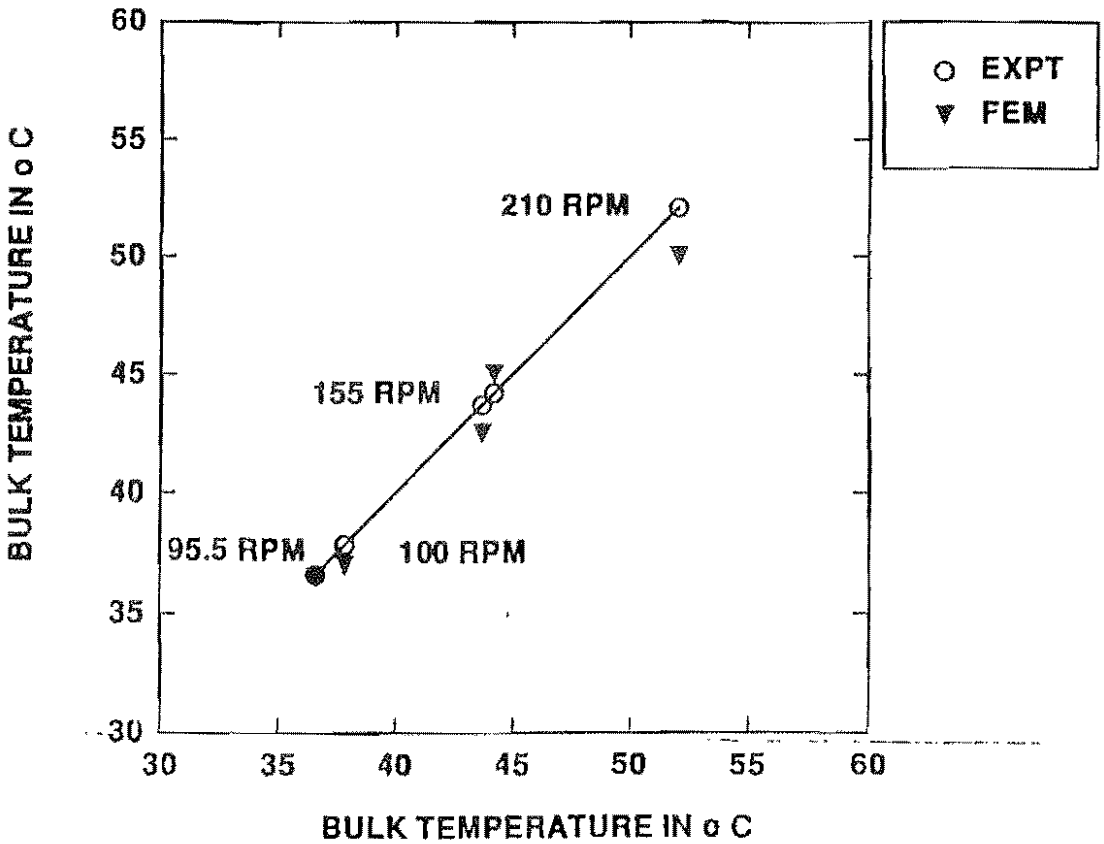
Pressure versus axial distance in a twin screw extruder obtained experimentally and from the Finite Element Method based mathematical modeling. The screw speed and the volumetric flow rate were 43.9 rpm and 11.8 kg/hr, respectively.





Pressure versus axial distance in a twin screw extruder obtained experimentally and from the Finite Element Method based mathematical modeling. The screw speed and the volumetric flow rate were 210 rpm and 13.3 kg/hr, respectively.

COMPARISON OF BULK TEMPERATURES



Die Design Considerations for Continuous Extrusion

Presented at

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Sept. 20 - 22, 1995

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As with most other engineering design problems, the configuration of a die for the continuous extrusion of any material is a function of compromises. The optimum design will be a trade off of features dictated by the the operational characteristics of the process, the safety considerations for the process and the limitations of manufacturing capabilities. A significant number of criteria must be taken into consideration when developing a die for a particular product and set of operating conditions. Additionally as you will likely discover, the die will give optimum performance only when functioning within the narrow band of operating parameters for which it was designed. In other words, there is no such device as a generic die which will give good performance under all operating circumstances for all products. In fact there is likely not a situation where a singular die configuration will give optimum performance with the same basic product under a wide range of operating parameters. As you will see, too high a rate or too low a rate may put you outside of the operating envelope for a die which performs very well with your product while you are operating within the dies' normal window of operation.

This paper is not intended to teach individuals how to be die designers. Moreover it is meant to enlighten those not well versed on the subject as to the critical factors which affect the performance of dies. It can also provide a check list of important items for someone who is given the responsibility of evaluating a die. Additionally it is intended to give some direction relative to finding help in addressing specific problems related to continuous extrusion of materials through dies to obtain the desired final geometric forms for end products.

Generally speaking, dies that are designed by empirical trial and error methods never get optimized. It will become obvious from the information presented in the remainder of this paper why that is a fact. The only way to optimize a die design for a given product and set of operating parameters is using scientific methods of mathematical or graphical solutions.

Having made that statement, the facts of life are, that the majority of dies in operation today were designed and developed using strictly empirical methods. They were developed by trial and error and the experience base of people who have worked in the industry for many years. This is true not only in the energetics' community, but also in every industry where dies are commonly used. There are two main reasons why this condition exists. The first reason is that up until very recent times, the technology hasn't existed to develop die designs by other than empirical methods. This situation has been remedied mainly because of the advancement in computer technology but also through the desire for improved efficiency and safety. These two criteria are becoming paramount to competitive production strategies. The second reason seems to be financial, in that the value of the effort to do scientific design to optimize performance is not readily visible to the personnel in many organizations who control the purse strings. Installed cost is intuitively obvious, but future production cost savings are a bit nebulous to define and in many cases hard to sell even when someone has the desire to sell them, which is not very often the case. This paper will give a few real life examples where significant cost benefits were achieved by optimizing die designs resulting in improvements in production rates at safer operating conditions.

Generally speaking, there are three primary variables which affect the extrusion process in continuous mixing and extrusion operations. These are :

THE PROCESS MATERIAL
THE FEEDING DEVICE
THE DIE

It should be understood that the design or performance of any one of these primary variables will affect the performance of the other variables and so they are directly interrelated and interdependent on one another. Therefore, the design of one component cannot be undertaken for optimum performance without evaluating it's impact on the other variables. This will become more self evident as we proceed.

The attributes of the primary variables which most affect performance are:

THE PROCESS MATERIAL. The most significant factor affecting performance attributable to the process material is the materials physical properties. The definition of these properties allows one to divide materials into types, all of which affect the extrudability of the product in a different manner. Four basic types exist (see Sketch 1-A).

NEWTONIAN Fluid, is a fluid whose viscosity does not change as a function of shear stress, shear rate or temperature within its fluid phase envelope. A typical example of this type of material is water. Water viscosity is constant between its freezing point where it changes to a solid and its boiling point where it changes to a gaseous material. Very rarely does one encounter an extrudable highly solids filled material which is Newtonian.

PSEUDOPLASTIC Fluid, is a fluid whose viscosity decreases as a function of increases in shear rate, and temperature. A typical example of this type of material is polypropylene. When polypropylene is in a fluid state, it gets thinner as it is subjected to higher shear rate. It should be noted that Pseudoplastic Fluids usually exhibit a Newtonian region at low shear stress values. DILATANT Fluid, is a fluid whose viscosity increases as shear rate increases, in effect it is the opposite of a pseudoplastic material. Clay dispersions such as Silly Putty make good examples of this type of fluid, if you let it lay in your hand, it will slowly ooze through your fingers, but if you knead and work it in your fist it will quickly become very viscous and tough. BINGHAM Fluid, is a fluid whose viscosity remains unchanged until it is subjected to a specific stress , then the viscosity will decrease as a function of the applied shear rate much like a Pseudoplastic. A typical example of a Bingham Fluid would be Ketchup. We've all had the experience of trying to get it out of the bottle, a few good raps to apply the appropriate amount of initial stress and it usually flows pretty freely. Once we stop pouring however, it takes a few raps to get it started again. It is worth mentioning at this time that highly filled materials such as those customarily used in the energetics' field can exhibit all four characteristic material types in the same material.

The physical properties of a material under given sets of stimuli are called the rheological properties, these properties when known will define the material type and the values of the physical properties for that material at the stimuli values. Typical useful information found in rheological reports for materials are the change in viscosity as a function of shear rate, shear stress and temperature. Unfortunately published data on rheological properties is pretty much confined to well known and simple polymers, while in the energetics' field complex , highly filled materials are the normal trend. There are places to acquire rheological data for unique formulas. A typical place where one can get help in this respect is Stephens Institute of Technology, at the Highly Filled Materials Institute (HfMI). Other facilities who are working on acquiring data on this type of technical level are The Naval Surface Warfare Center at Indian Head MD. and ARDEC at Picatinny Arsenal in Dover NJ. With some experience, one can combine the rheological characteristics into a mathematical model such as a Hershel-Bulkley equation which can then be combined with other mathematical models and equations to predict performance of screws and dies (see Sketch 2).

The one characteristic of a material which has not been addressed until very recent years has to do with the adhesion characteristics of materials to other materials and hence affects the wall slip of the product in screw and die applications. HfMI @ Stephens has developed the ability to quantify wall slip under various conditions, and within a given set of parameters can provide a mathematical model to attach to the Hershel-Bulkley equation to make it complete for any process.

Another physical property of the product that will affect the performance of the extrusion system, especially at the die is the product consistency (homogeneity). This characteristic is a function of the precision of the neet ingredient feeding systems and of the efficiency of the mixing device. True uniform distribution of ingredient within a properly developed matrix binder system in a consistent manner is essential for optimum die performance.

This brings us to the second major variable in the extrusion process; THE FEEDING DEVICE. This term does not refer to the feed systems for the neet ingredients, but rather to the screw device feeding the die itself. The efficiency of the system at this juncture is dependent on how well the extrusion system has been married to the die and to the process materials' rheological properties. The most well designed Die will not perform with any degree of efficiency if the extruder screw trying to feed the material to it has been improperly designed for the application.

Most continuous process systems incorporating extrusion are currently of the single screw or co-rotating twin screw design. Both of these devices are drag flow systems. Drag flow devices pump materials as a function of the frictional forces between the rotating bodies of the screw flights and the internal barrel wall of the extruder. As such, these devices are not positive displacement and rely heavily on material adhesion and viscosity to pump at optimum efficiency. There are literally thousands of screw designs on the market for these types of machines. Most of these designs have been developed imperically for a given material type and a given set of operating conditions. It is quite common to develop a screw for a new process by reverting to something that has been used successfully in the past and tweaking it for the new product. Traditionally most operators have little knowledge of what processes occur in the screw channels within their machine and hence have no way of knowing whether improvements in performance can be achieved over their current design. In reality however, more work has been done in the evaluation of extruder screw designs by mathematical models and computer generated graphical models than in any other area of mixing and extrusion. This is particularly true with reference to the screws ability to transport materials which are homogenous and whose rheological characteristics can be defined. In the channel of a screw, the following flow characteristics are occurring simultaneously (see Sketch 1-B): Drag Flow, this phenomena causes the material to be transported down the barrel in the screw channel. Pressure Flow, this phenomena causes the material to flow cross channel within the screw. Wall Slip which is the loss in flow due to the loss of adhesion between the process material and the wall of the extruder. The real net flow then is equal to Drag Flow-Pressure Flow-Wall Slip (see Sketch 1-D). Because these are not positive displacement devices, as pressure flow increases, drag flow decreases and as wall slip increases drag flow also decreases. Under certain circumstances, a machine that will put out an acceptable thruput with an open discharge may put out virtually no flow when a die is introduced onto the machine and a substantial back pressure is applied. Items in the screw and barrel design which most affect the ability to pump material are, the screw lead, the number of flights and the clearance between the screw and the barrel and the mating screws if the unit is a twin screw design. Generally speaking longer leads pump higher volumes while shorter leads pump against higher back pressures, also tighter clearances offer better pumping as there is less leakage and multiple flights usually improve pumping against back pressure.

Another key area of the feeding device is the transfer zone, where the extruder screw ends and the entrance to the die begins (see Sketch 1-C). This area is very important relative to the efficiency of the extrusion system.

If this annulus is long it can provide significant pressure drop in the system, if it is to large, the shear rate in it can drop dramatically affecting the viscosity in this region and providing a significant change in material properties. It can also provide regions of high and low shear rate areas which will cause eddy's in the product flow path that will induce unmixing of the product in the die entrance creating extrusion of disuniform mass and geometry. When designing an extrusion system, it is just as important to model the flow through this region using the appropriate mathematical models as it is to evaluate the screw and die areas of the system.

The last critical item relative to the feeder device, and this applies to the die as well, is the thermal control of the system. As the physical properties of the process material in many cases is dramatically effected by the thermal properties of the system, control of the system temperature is a very important criteria in the extrusion system performance. The ability to transfer heat quickly and effectively as well as the requirement to maintain a stable constant thermal environment are key elements in providing optimum extrusion. Whenever possible it is best to try to design a system that will come into true thermal equilibrium without additional heat transfer from a jacket (i.e. run the system adiabatically if possible). This is not always possible as in the case where thermal plastics are used as binder systems and the use of solvents is not desirable. In this case a combination of horsepower heat input and external heat thru jackets is a necessity to achieve both product features and process variables required to produce the proper production conditions.

This brings us to the last variable the DIE. One key element of the die is usually dictated by the requirement for the final end product and that is the geometric shape of the extrudate. There is normally not to much that one can do with this particular part of the die except to keep it as streamlined as possible and to keep the length as short as possible. In some extreme cases, it is not possible to make the final geometric shape in a continuous extrusion. When this occurs, the alternate of a cast or batch extrusion process are normally pursued. In some cases slight alterations in either formulation or geometric form will allow an item to be continuous extruded that would otherwise normally have to be cast. For the most part the remainder of the die design is truly dependent on the materials rheological properties and on the desired operating condition such as flow rate, pressure drop and temperature rise. Typically streamlined, minimum angle entrance and exits to the die body generate the optimum characteristics of minimum pressure drop and lowest temperature rise. Remember, perfectly mixed(truly homogenous) and properly degassed process material cannot be consolidated any further in the die at any discharge pressure. Never attempt to generate pressure at the die simply to consolidate material, if it's not consolidated when it gets to the die then fix the mixer. The best extrusion is normally achieved at minimum pressure drop and lowest temperature rise, this is when the die is operating at its highest efficiency. Exceptions to the general rules always exist and a typical example of this is when dealing with Bingham fluids. Bingham fluids need a minimum shear stress (i.e. minimum shear rate in order to achieve fluid flow in a stable manner). In the case of many Bingham fluids, streamlining to improve flow may be a self defeating condition. For example, a few years ago we had the pleasure of working on a project involving a carbon filled material that was to be extruded in the form of a cylindrical rope with a hole the shape of a star in the middle (see Example 1). The outside diameter of the rope was critical and had to be held to within .003 inches as extruded.

The outside diameter was to be .375 inches with the star shaped hole being 8 points with a root diameter of .045 inches and the star O.D. being .100 inches. We designed and built a streamlined die (see Sketch -3 & -4) and when we ran the material through a twin screw extruder the die flow would run smoothly for a few minutes, then it would slow and eventually stop. After a few moments the die would open up and material would flow again. This condition would repeat many times, eventually the die would plug off and quit for good, at which point the mixer would backfill and the process would stop. When this occurred, the temperature had usually risen outside of the acceptable envelope and the extrudate would be disuniform in both consistency and mass. We were the fourth extruder company that the client had run trials with and the previous three never got the material to come out of the die. The customer was beginning to believe that he had a process that was not achievable under any circumstance. We convinced him to consult with Steven's Institute/ HfMI on his formulation. Steven's did a rheological analysis and we discovered that the material we were dealing with was a Bingham fluid which required a minimum shear rate at our process conditions in order to maintain a uniform flow property. We redesigned the die which was borderline for this process even when it was completed correctly. This was due to the fact that the final geometric shape could not be altered and it did not give us much margin of safety factor to keep the shear rate above the minimum required for stable extrusion. The redesigned die (see Sketch -5 & -6) did however make the process work and three production lines were ordered and put into service on this formulation. The final dies did not look like the streamlined prototype because we had to build in an inefficiency to make them work. An interesting follow up to this example came about a year later. The customer called and said that there was something wrong with the process. He said the material coming out the die was surging for the past few days on one of the machines and the day he called me it had stopped extruding and began backing up the vent tube. The machine that this condition existed on was the first machine in operation and had the most hours on it. We asked him to measure the die components, especially the die hole and the star shaped perf. The die had grown a wear pattern which had caused it to become about .010 inches oversized in the perf. entry area of the die. This area was the critical annulus for flow with a very narrow margin of tolerance for shear rate drop. We referred to the numbers we had been given a year previous by HfMI and redid some calculations. It turned out that at .010 inches of additional clearance the shear rate dropped the shear stress below the critical point on the rheology curve and material would quit flowing. We had the customer send the parts out and had them chrome plated .010 on a side. He then reinstalled the parts and the process worked flawlessly. After that he ordered a set of spare parts and whenever he had a problem with the process diminishing, he would pull the parts in process and replace them with the spares while he sent the originals out for plating. The optimum die design for this process was obviously one that was not able to give the lowest pressure drop and temperature rise, because that optimum would not let the process run due to other causes.

Some other key points on the geometry of a die, avoid steps (discontinuities), avoid fast transitions, and avoid steep angles, all of these items cause pressure drop as well as eddy currents and widely fluctuating shear rate zones. These cause unmixing and change in the product consistency. Deaerate the product completely, gas and air entrainment change the rheological properties of the product and also cause serious wall slip.

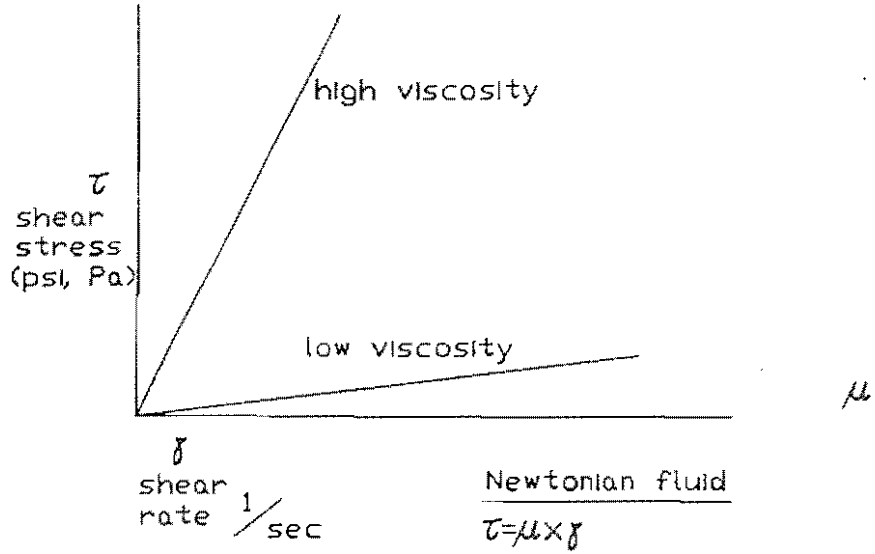
There are some very good mathematical models and graphical models out that can be used to calculate die flow characteristics. These will evaluate pressure drop and temperature rise for a given set of rheological characteristics at a given thermal condition and a given rate. It is best to let the experts at places like Stephen's HfMI gather the rheology data and feed the graphical models with the data to evaluate a particular design. Another approach to the problem of process improvement is to look at real process data and to evaluate the change to a die design as a function of previous performance (i.e. if this is the data for the existing die, and assuming the process is isothermal, then if I make the following design changes , the die performance will be approximately "X"% better). This can be done by plotting the cross section of the die and interpolating the overall pressure drop through the die as a function of each cross section element reviewed (see Sketch -8). By modifying the elements of the cross sections and replotting the overall, one can develop a plot of the theoretical improved performance of the whole. This process will work very well if one does not cross a threshold (i.e. the change point in rheology where the material goes from Pseudoplastic to a Bingham fluid).

In addition to the process parameters, the designer must concern himself with the mechanical integrity of the die. One must look at the strength members of the spiders, pins, center perforations etc. The flow direction of materials greatly affects some of these items. For instance we did a die design for Hercules Sunflower Kansas for a 7 perf die for LOVA. This die worked exceptionally well and was very efficient. We used Steven's HfMI for materials properties and designed a die for optimum extrusion performance. It worked very well. They then asked us to do a 19 perf die. We used the same basic design as for the 7 perf. The major difference being the number of pins and the size of the pins (see Sketch -9). The pins in the 19 perf die squeezed into the middle and gave a non-uniform pattern of perforation. We found that the only way to eliminate this was to square off the exit angle to be normal to the axis of the pins at the holding point (see Sketch -10). If we gave the exit any kind of an angle to help reduce pressure drop at this point, we caused the pins to move. The final compromise was an entrance angle to the capillary that was normal to the center of the pins and a spherical radius leading into the the capillary chamber (see Sketch -11). Because of the very small diameter of the pins .010 inches, even with a .030 inch base for rigidity, there was no opportunity to utilize the more efficient long tapered exit entrance to the capillary. Every attempt to do this caused the pins to deflect beyond acceptable limits. However, we were able to incorporate all the upstream modifications to the die that we had instituted into the previous die design. The final configuration was tested at Hercules in New Jersey and the die produced a pressure drop 140 psi lower than the conventional die they currently had in service.This was accomplished with 20 degree F lower temperature rise as well.

This experiment was conducted using a ram extruder. This is a batch operation and more efficient from an extrusion standpoint than a continuous screw processor. It should also be noted that dies which perform very well in ram extruders mat not perform well in a continuous process. A Ram extruder usually extrudes a single charge of material at which point the ram is withdrawn with any unextruded material and recharged. This does not allow for the build up of material in low shear rate zones because the time and material processed have not provided opportunity for product build up.

If one has worked for any length of time in extrusion where continuous process systems are used, you will probably have noted on at least one occasion removing a die and finding a cone of material built up at the entrance of the die. This cone usually represents the optimum entrance angle to the die and was formed naturally by the material when higher density constituents of the product fell out of the mix at the low shear rate areas and formed the new entrance geometry. The die likely performed at almost optimum conditions in that area after the new cone emerged. Unfortunately we don't want, nor can we stand to have that build up occur in a die used for energetics materials. This condition could pose a significant safety risk and is not desirable. It is more desirable to have a die that is properly designed for the process and to run the process the way the system was designed to have it run.

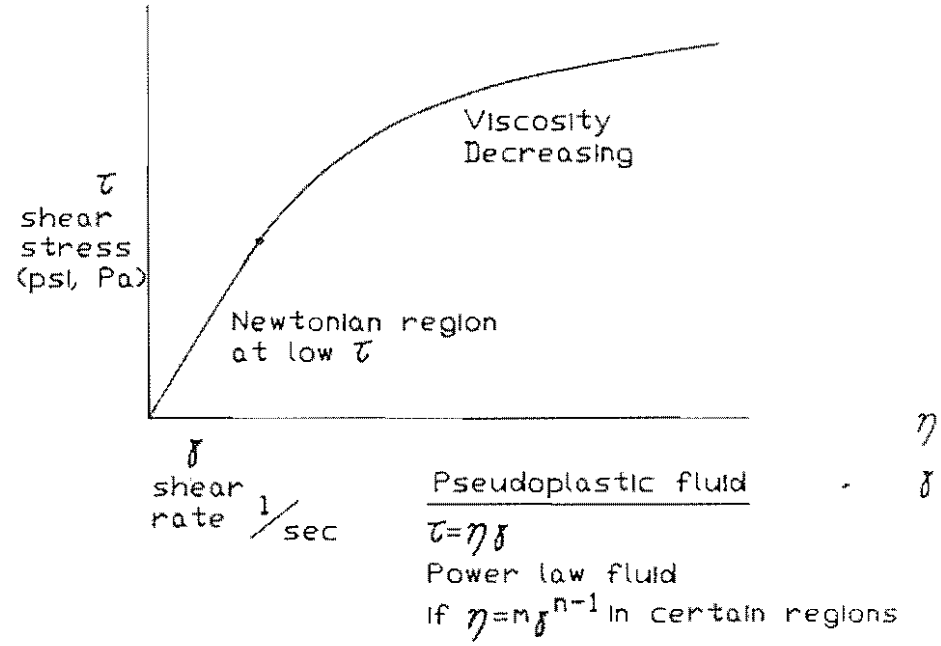
There are obviously many more specific design details involving the PROCESS MATERIALS, the FEEDING DEVICES and the DIE than what could be covered in this brief overview. In fact many books have been devoted to each of these subjects. However, I hope that this paper has helped to enlighten you on a few of the more key aspects of extrusion and I hope that you have become aware that the process is complex, that it involves many facets that are interdependent and that there are places where you can acquire help in solving your unique extrusion processing problems.



Newtonian fluid

$\tau = \mu \times \gamma$

is constant

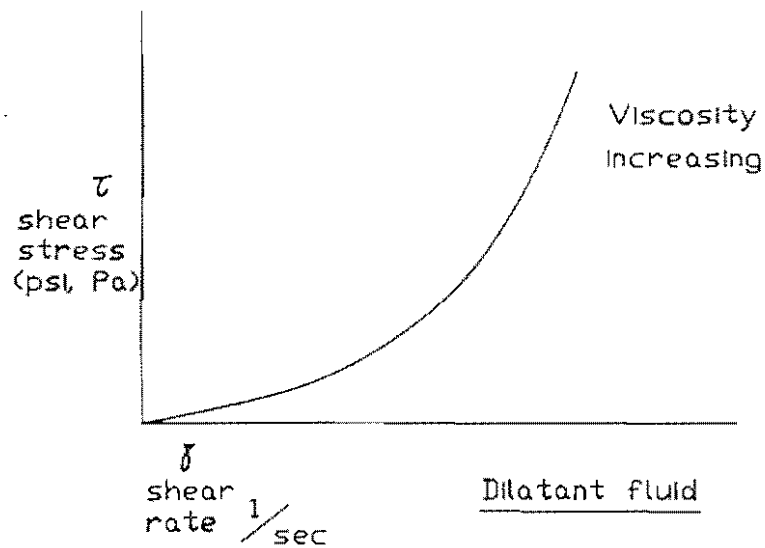


Pseudoplastic fluid

$\tau = \eta \gamma$

Power law fluid

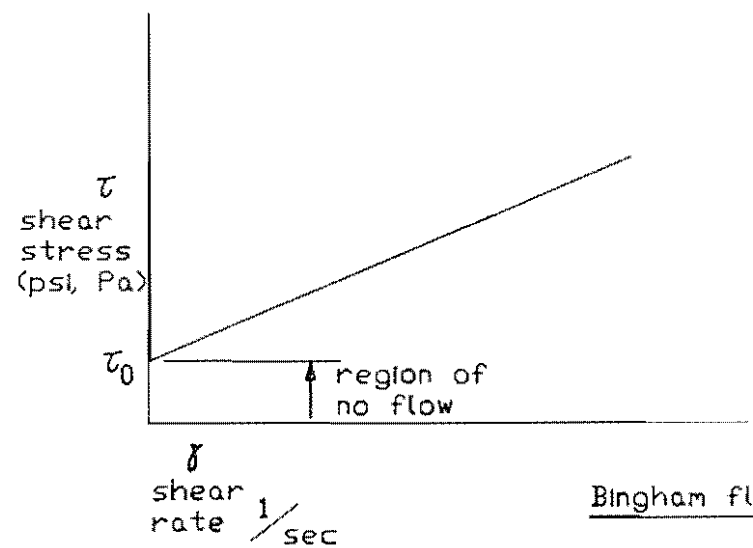
If $\eta = m\gamma^{n-1}$ in certain regions



Dilatant fluid

Clay dispersions

Silly putty

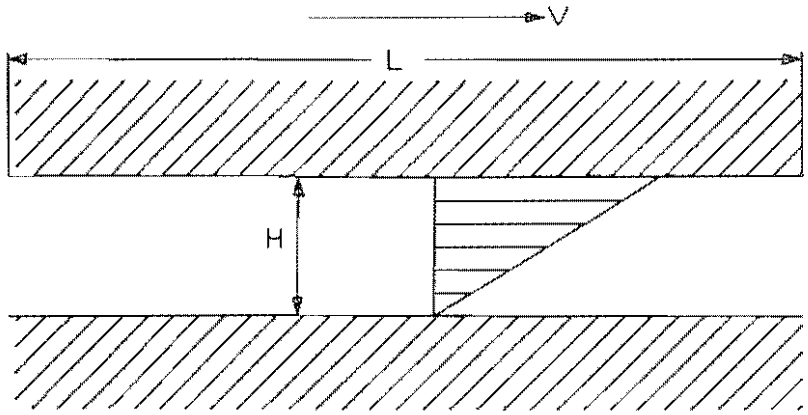


Bingham fluid

Ketchup

SKETCH

1-A



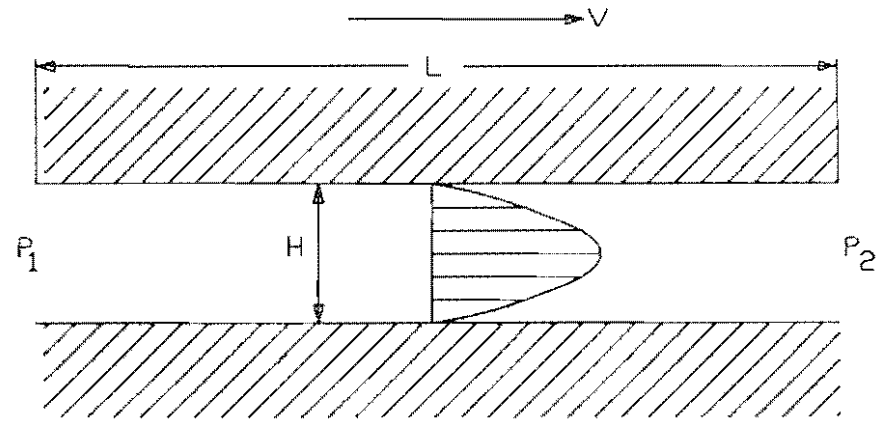
Drag flow

Shear rate $\gamma = \frac{V}{H}$

Shear stress $\tau = \mu \gamma$

Flow rate (per unit width): $Q = \frac{VH}{2}$

Force (per unit width) $F = L\tau$

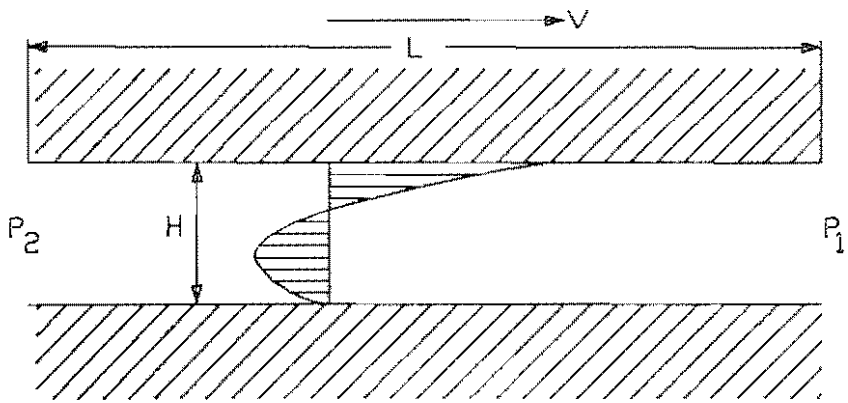


Pressure flow

Shear stress (τ_w at the wall) $= \frac{H(P_1 - P_2)}{2L}$

Shear rate (γ_w at the wall) $= \frac{H(P_1 - P_2)}{2\mu L}$

Flow rate (per unit width): $Q = \frac{H^3(P_1 - P_2)}{12\mu L}$

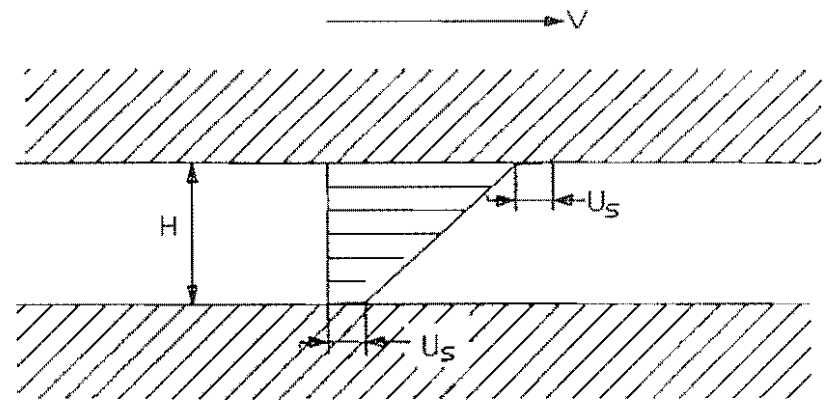


Drag- and pressure flow

Shear stress at the wall:

$$\tau = \frac{V}{H}\mu \pm \frac{H(P_1 - P_2)}{2L}$$

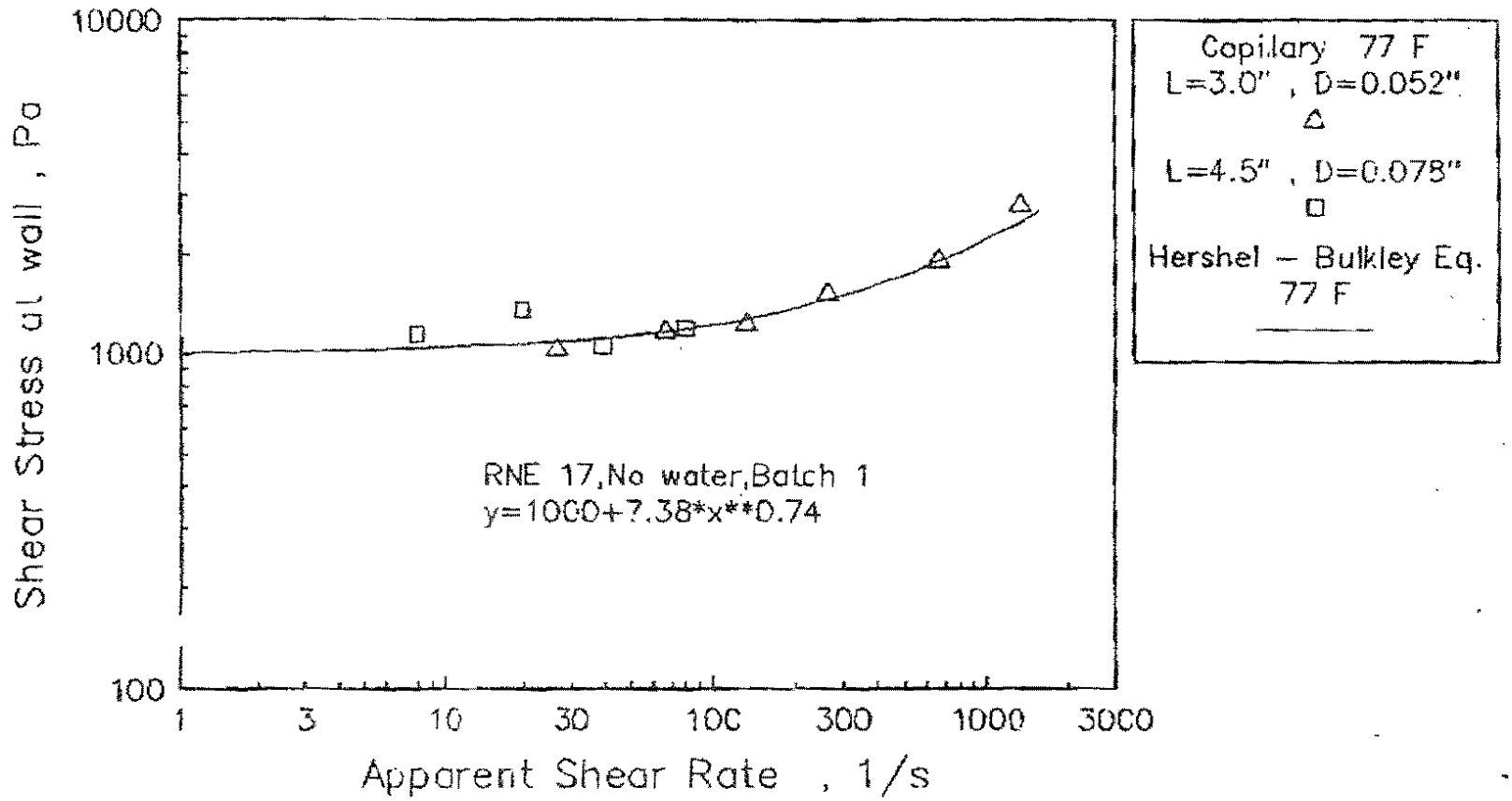
Flow rate (per unit width) $Q = \frac{VH}{2} - \frac{H^3(P_1 - P_2)}{12\mu L}$



Wall slip

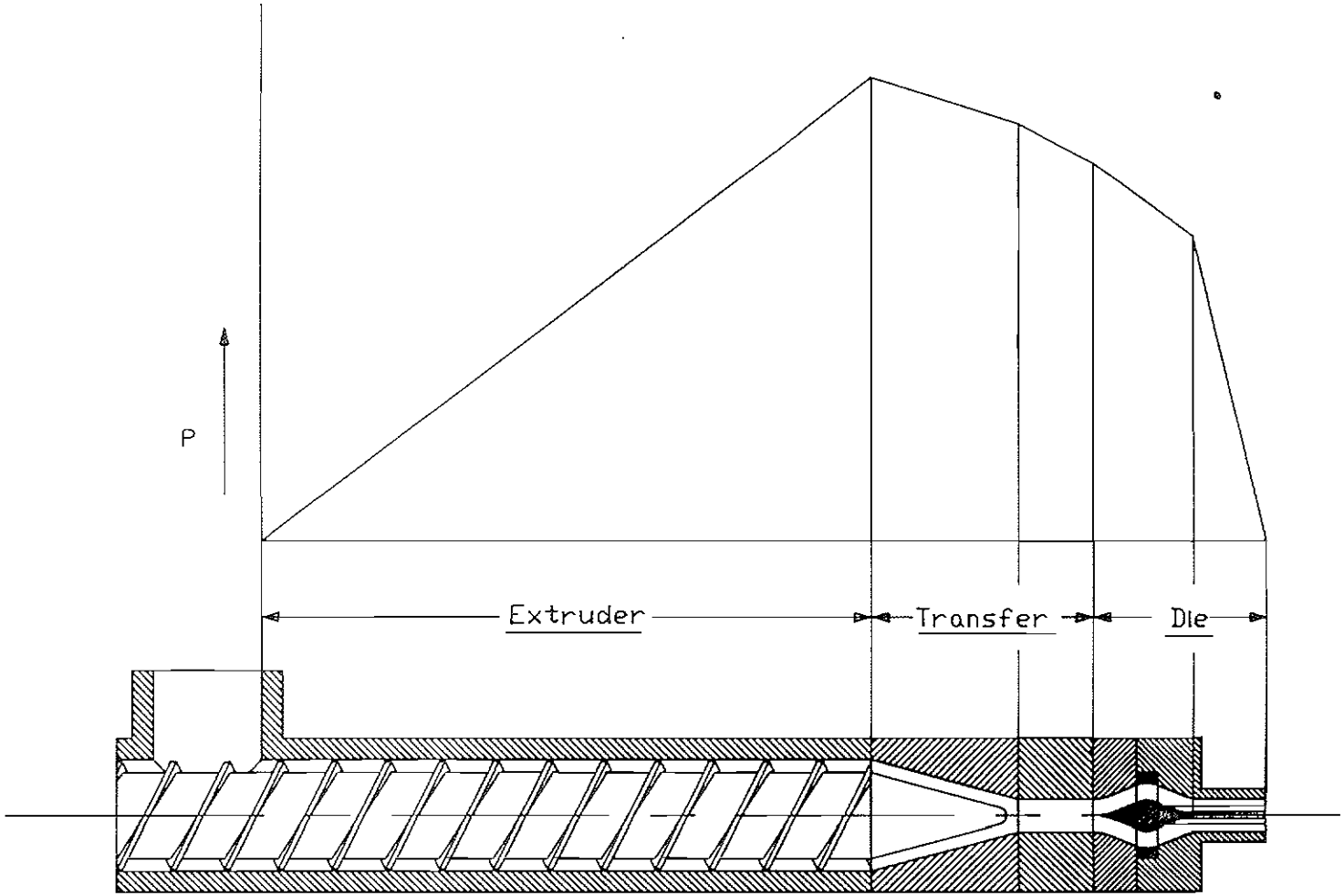
$$U_s = C_1 \tau_w^{n_1}$$

SKETCH 1-B



SKETCH -2

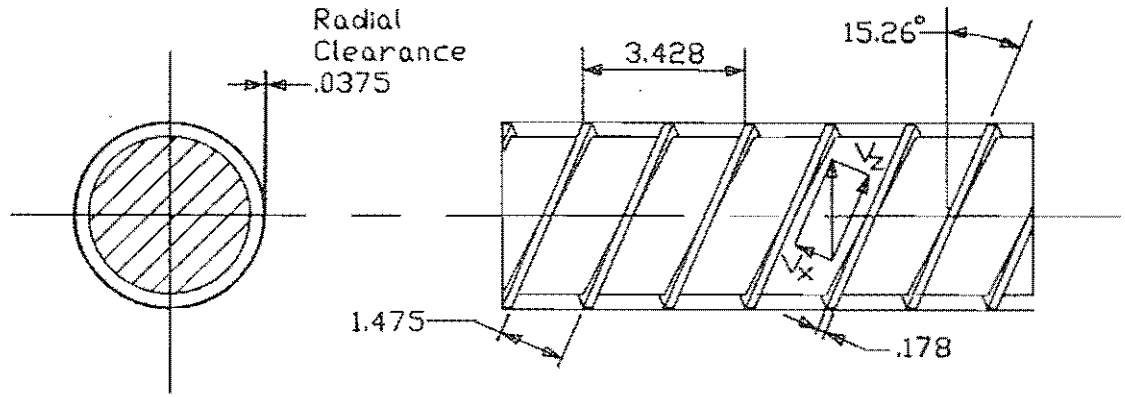
TYPICAL EXAMPLE BINGHAM FLUID



Schematic pressure diagram

SKETCH
1 – C

A.S.R.M. Extruder screw data



Geometry

$$Q = A*n - B\frac{\Delta P}{\mu}$$

$$A = \frac{W*(H-c)*V_z*2}{2}$$

$A = 4.48\ in^3$

$$B = \frac{W*H^3}{12*L}2$$

$B = .000134\ in^3$

Viscosity

$$\eta(\gamma,T) = \sigma_0(T) + k(T)\gamma^{m(T)}$$

$$\sigma_0(T) = -55.2 + 2.17T$$

$$k(T) = 1.09*10^4 - 113T$$

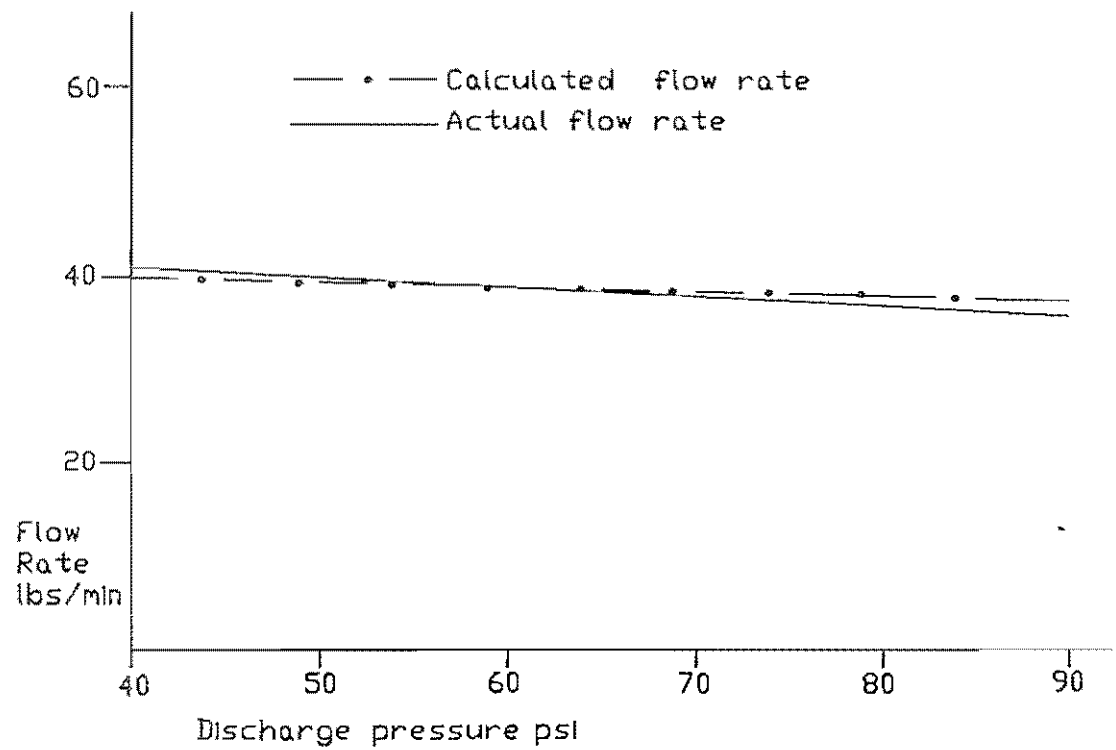
$$m(T) = -0.141 - 1.76*10^{-4}T$$

Wall slip

$$\tau_{w,PA} = 13860 + 200\gamma_w$$

$$Us_{mm/sec} = 0.0016\ \tau_w^{0.805}$$

Results



Example of calculated flow-vs-actual flow

SKETCH 1-D

CARBON PASTE

Requirement: Continuous extrusion of perforated rods of homogenous carbon with specific mechanical properties. Tolerance of .195 inches rod ≈ +.000 - .003.

Problem: Flow instability at the die with multiple strands, variations in mechanical properties.

WE worked with the customer and HfMI at Stevens, and optimized process.

Material was found to be:

a) Bingham fluid
b) Pseudo-plastic within a range of temperature and shear stress.

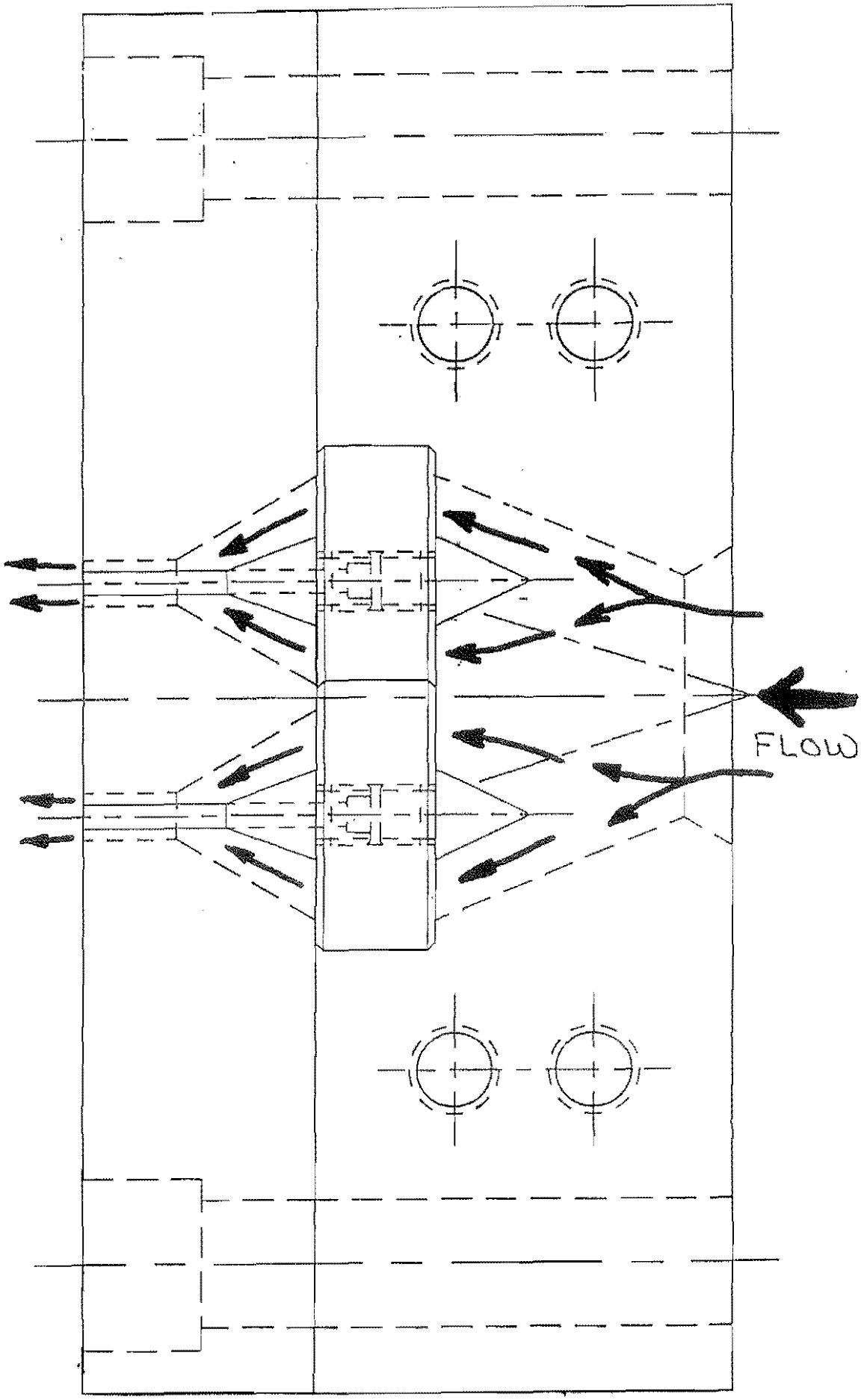
Completely redesigned extruder screws and dies to always perform in the pseudo-plastic range.

Put a 50 mm pilot plant in operation and three (3) 80 mm production units.

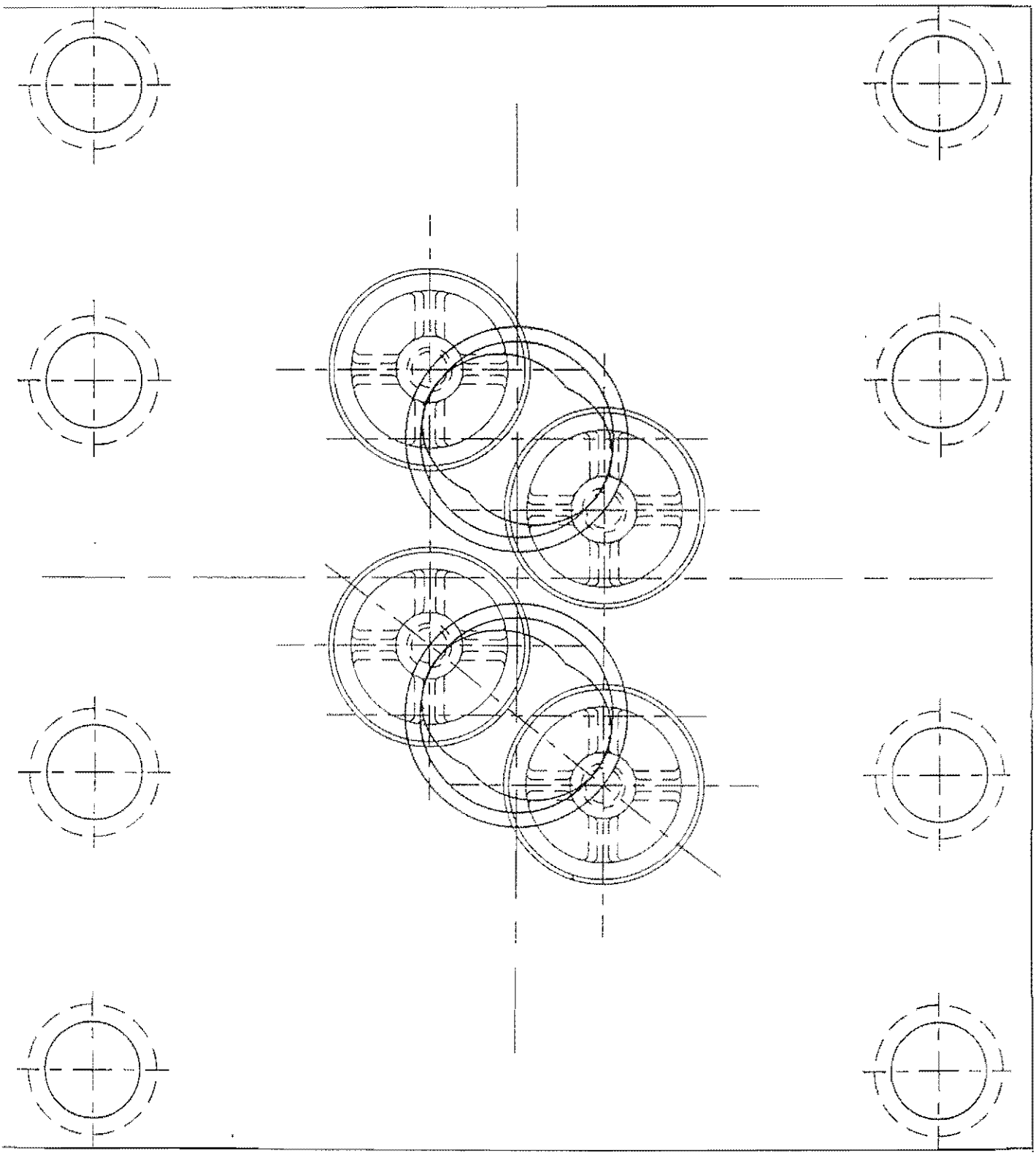
(NOTE: Machines have run for three (3) years with exceptional performance.)

Operational band is so tight that .010 inch wear in the die entrance caused the process to cease and become unstable. Chrome plating worn parts corrected this problem.

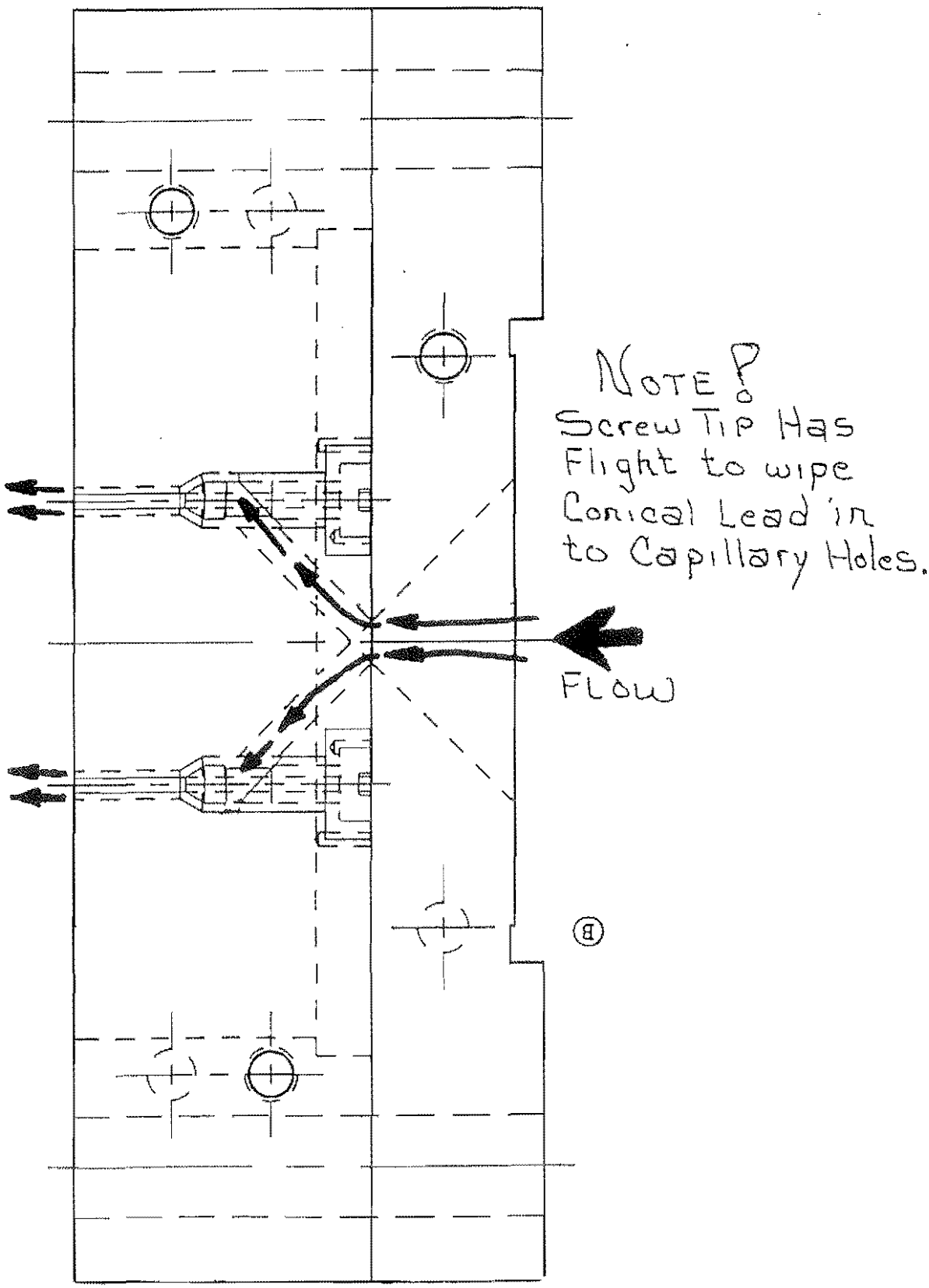
EXAMPLE - 1



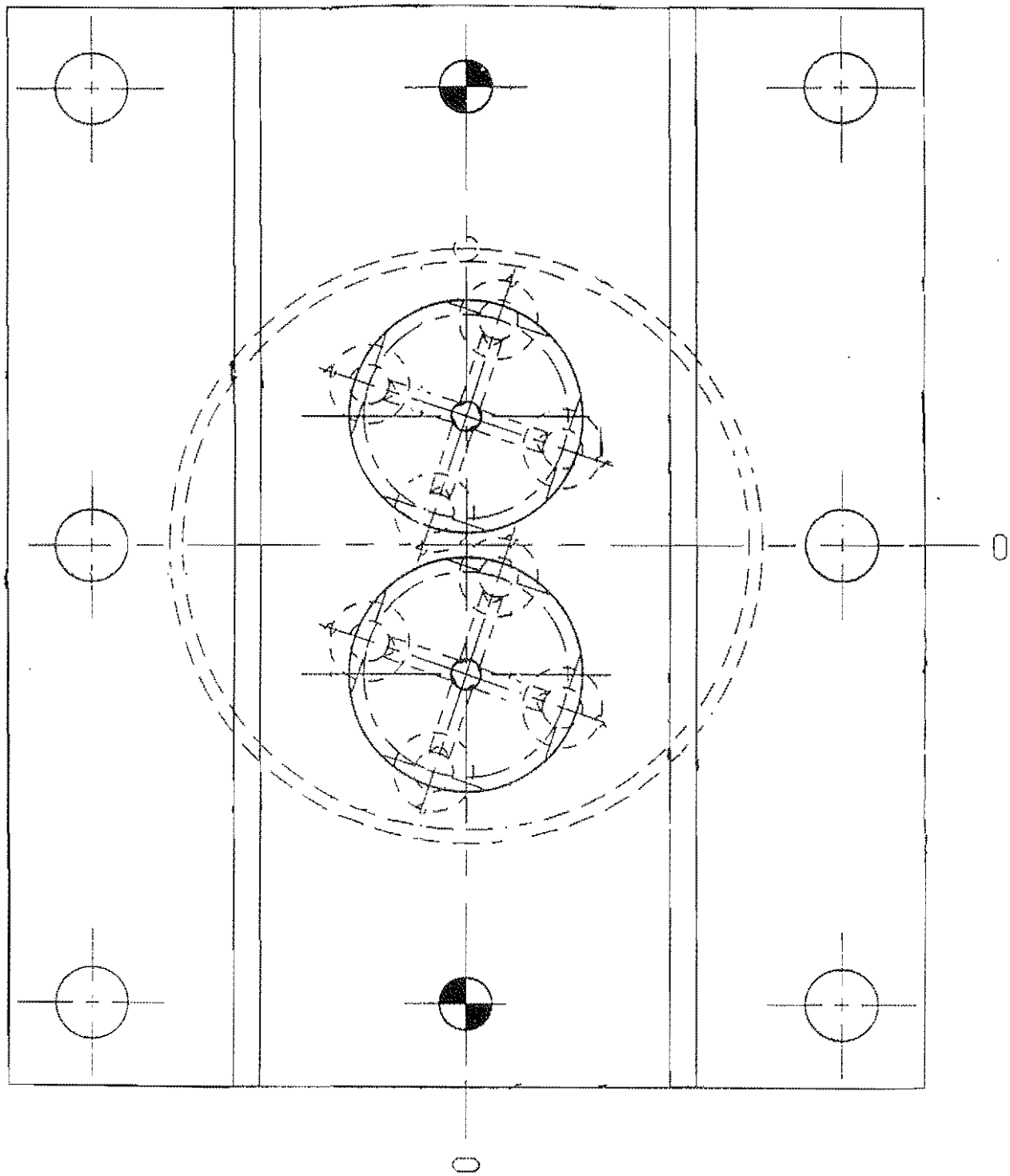
SKETCH-3



SKETCH-4

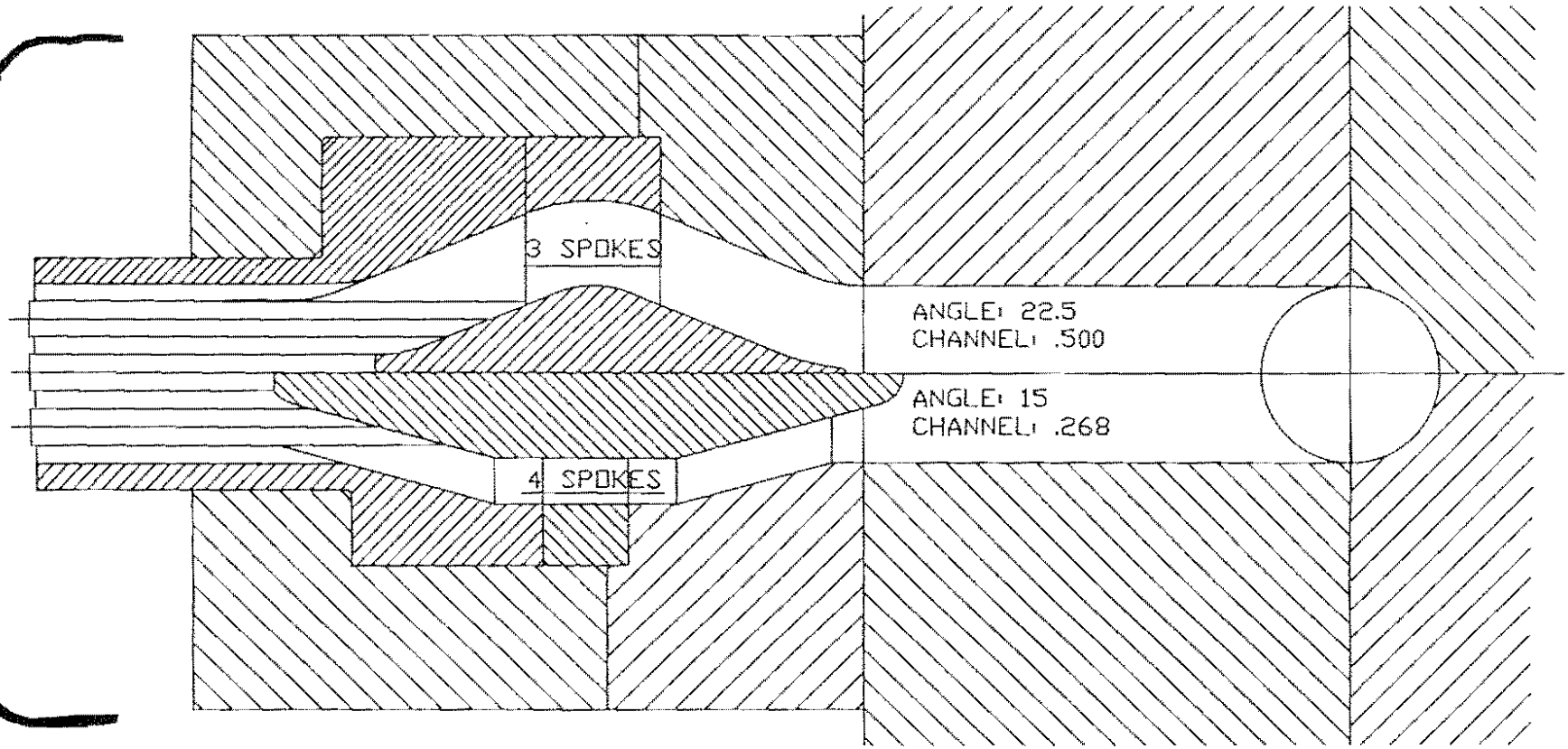

NOTE!
Screw Tip Has
Flight to wipe
Conical Lead in
to Capillary Holes.
FLOW
B

SKETCH -5



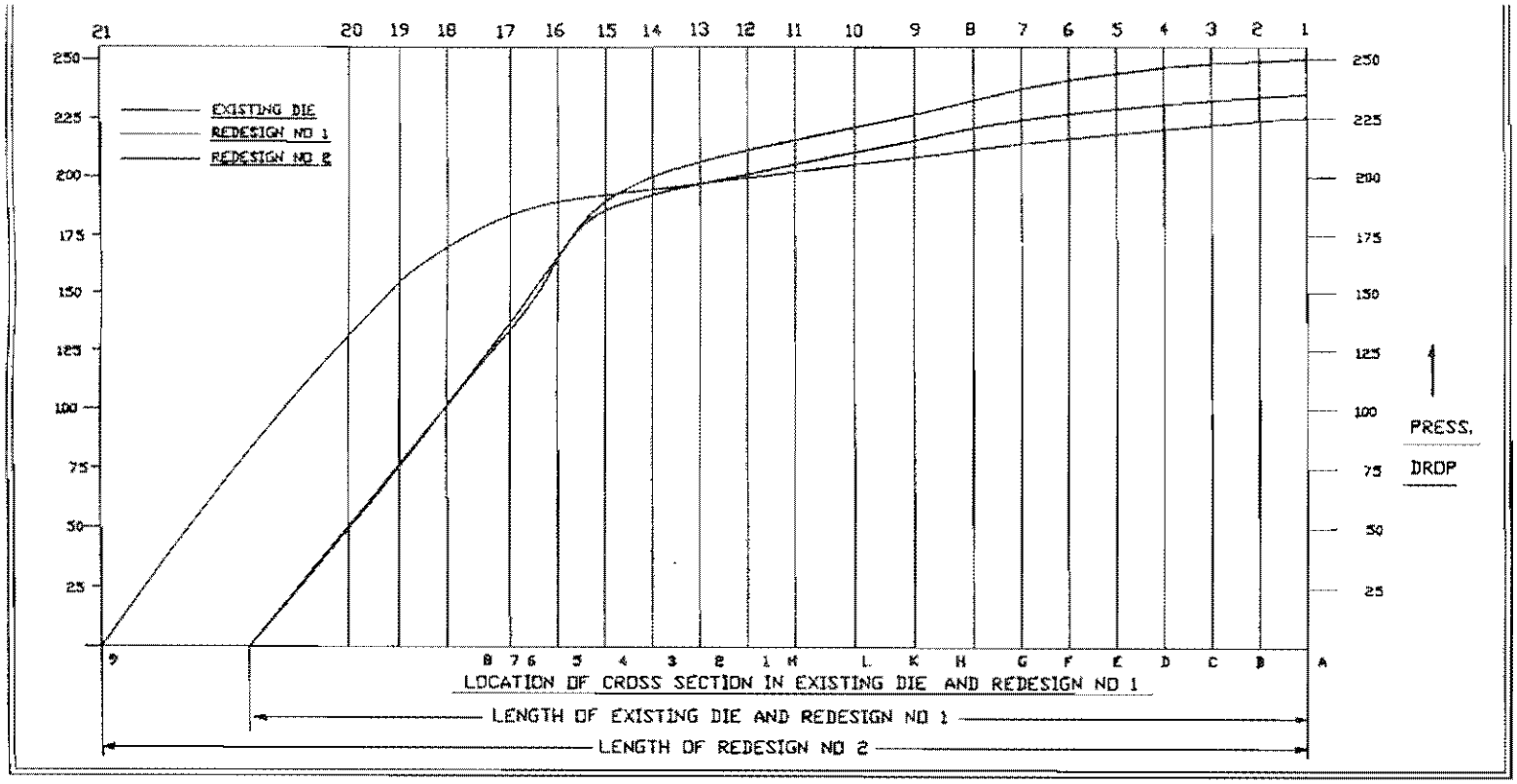
SKETCH 6

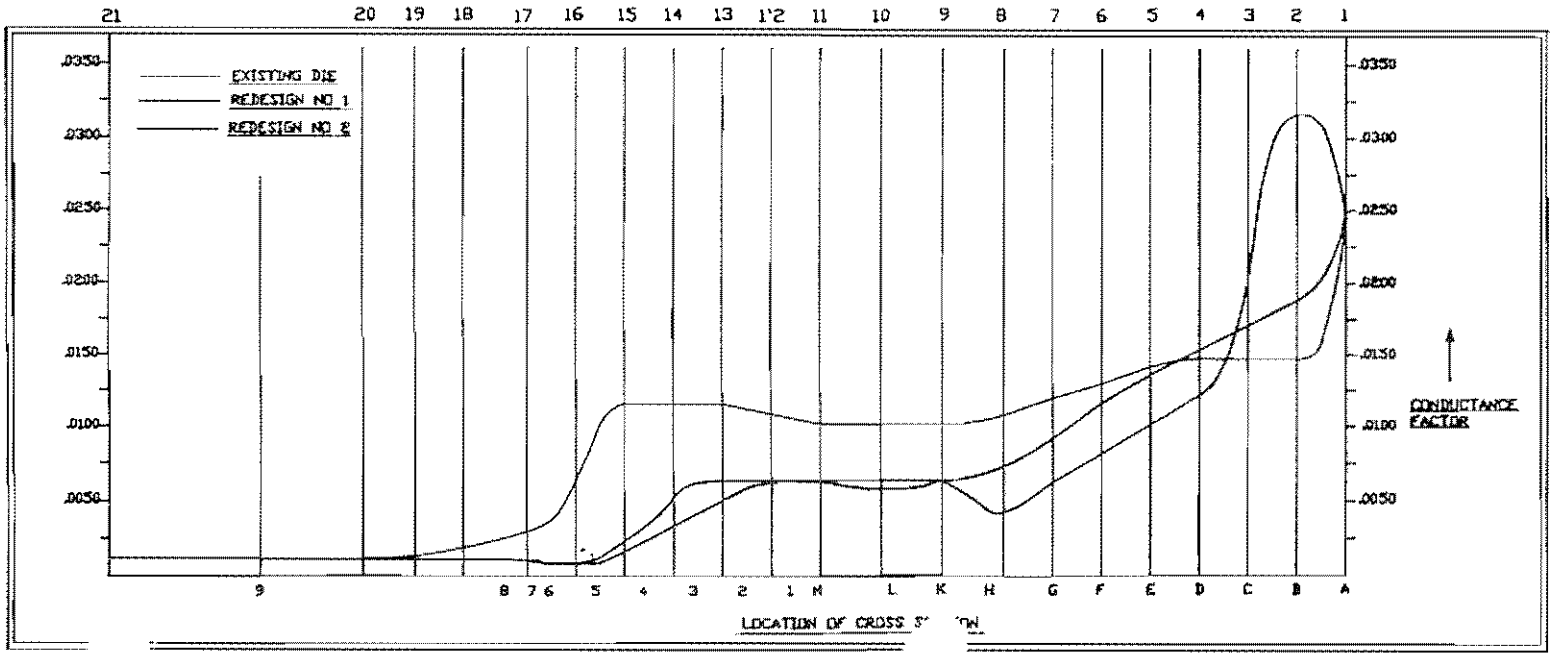
NEW DIE DESIGN



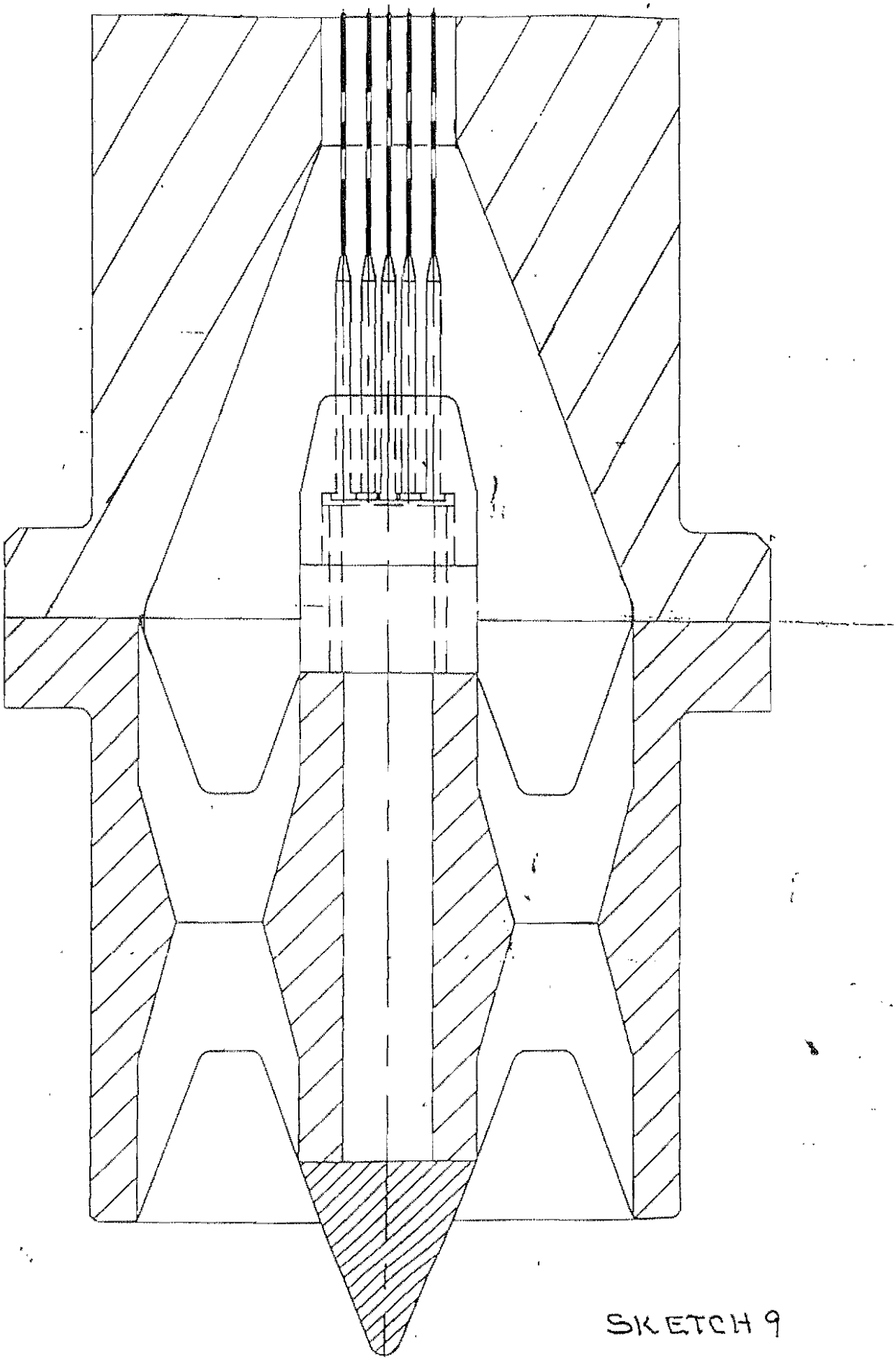
OLD DIE DESIGN

SKETCH - 7

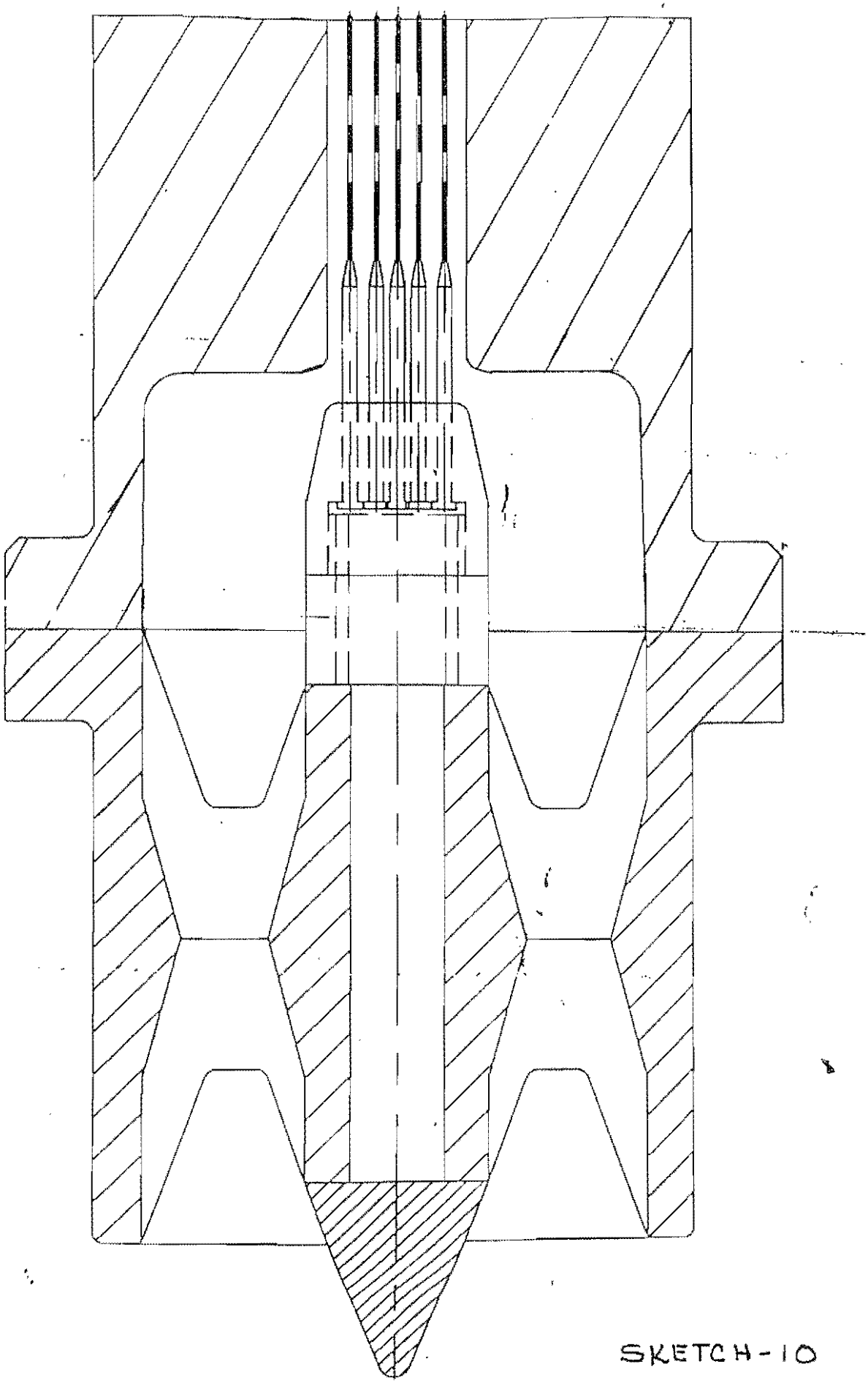

EXISTING DIE
REDESIGN NO 1
REDESIGN NO 2
PRESS. DROP
LOCATION OF CROSS SECTION IN EXISTING DIE AND REDESIGN NO 1
LENGTH OF EXISTING DIE AND REDESIGN NO 1
LENGTH OF REDESIGN NO 2


EXISTING DIE
REDESIGN NO 1
REDESIGN NO 2
CONDUCTANCE FACTOR

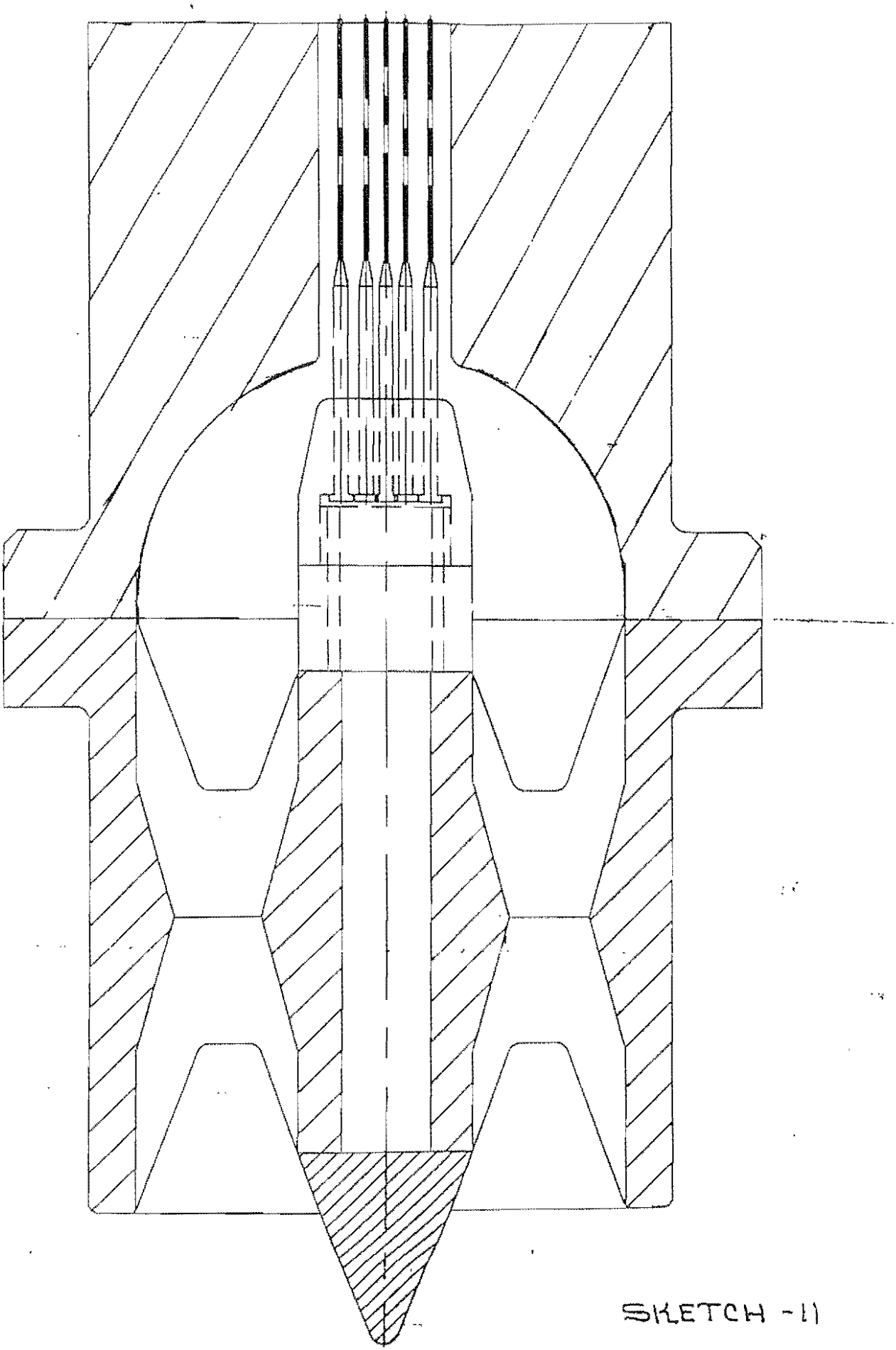
SKET 1-8



SKETCH 9



SKETCH-10



SKETCH -11

Upgrade The Continuous Processing Facility at IHDIV, NSWC

Naval Surface Warfare Center
INDIAN HEAD DIVISION

Naval Sea Systems Command

Richard S. Muscato
21 September 1995

Naval Surface Warfare Center
INDIAN HEAD DIVISION
Naval Sea Systems Command

Upgrade Continuous Processing Facility

Objectives

To Design and Upgrade the Twin Screw Extruder Facility Capabilities in Preparation for the CPOCP Project

To Construct a Facility that is Versatile and Flexible for Processing a Variety of Products

Naval Surface Warfare Center
INDIAN HEAD DIVISION
Naval Sea Systems Command

Upgrade Continuous Processing Facility

Oct 93	Start Construction
July 94	Complete Checkout/Debug
Aug 94	Reinstall DAS and Adjustable Slit Die Rheometer
Sept 94	Complete Process Review Board
Oct 94	Conduct Live Start Up Operations

Naval Surface Warfare Center
INDIAN HEAD DIVISION
Naval Sea Systems Command

Upgrade Continuous Processing Facility

Additional Capabilities

Solid Refill Systems

Additional Solid Feeder/ Liquid Feed System

Extruder Barrel Temperature Control (5 Zones)

Product Takeaway Area

Integrated Dehumidification System

Fire Detection/Protection System

Naval Surface Warfare Center
INDIAN HEAD DIVISION
Naval Sea Systems Command

Upgrade Continuous Processing Facility

Additional Capabilities

EPA Compliant Exhaust Ventilation System

Adjustable Slit Die Rheometer Capability

New Control Room

Upgraded Data Acquisition System

Two Nitrogen Pressurized Liquid Feed Systems

Eighth Annual

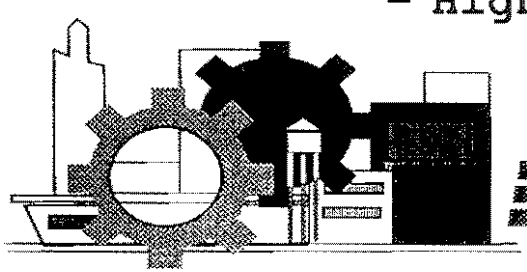
Continuous Mixer and Extruder Users' Group Meeting

OPEN DISCUSSIONS

Keywords:

Safety Issues

- Over Pressure Protection
- Access to Processing Elements
- Foreign Material Protection
- Percent Solids by Volume
  - Feeder Control
- Alarms/Interlocks
  - High Temperature
  - High Pressure
  - High Torque



- Segmented Shaft
- Cantilevered Shaft
- Elimination of Dead Spots
- Explosion Proof Motors
- Water Deluge
- Metal-to-Metal
- Viscous Shear Heating

Eighth Annual Meeting of the Continuous Mixer and Extruder Users' Group
September 20-22, 1995

OPEN DISCUSSION: RHEOLOGY

Wednesday, Sept. 20, 4:15 - 5:30 p.m.
Led by Dr. Andrea Chow, Lockheed Martin Missiles & Space
and Dr. Dilhan Kalyon, Stevens Institute of Technology

Summary of Discussion

Andrea Chow began the open discussion with a short introductory comment by echoing John Brough's meeting opening remarks that understanding the material rheology was beginning to be recognized by the energetics processing community as an essential element in continuous processing. However, many outstanding technical issues concerning rheology of filled materials remained. To facilitate the discussion, Andrea Chow compiled a list of rheology issues including:

- Accuracy & reproducibility of viscosity measurements
- Shear rate dependence of viscosity: are current method adequate?
- Rotational versus capillary viscometers
- Importance of other rheological functions (e.g., normal stresses, yield stress, apparent wall slip)
- On-line rheology monitoring

Dilhan Kalyon remarked that we had to differentiate what was the purpose of rheological characterization--quality control or process design. John Brough commented that we clearly needed both. The forum was then open to the floor.

In the first part of the discussion period, most of the discussion centered around using rheological characterization for process development and design purposes. Several people shared their experience of successful and unsuccessful uses of rheological data to assist process design. In one case, the data combined with numerical simulation to analyze a screw section of a deaerator gave very good agreement with actual process data. In another case, applying mix viscosity to a slit plate design analysis suggested an erroneous conclusion that casting through a slit plate could not be achieved. The moral was that the "correct" rheological measurements must be used.

A sentiment was expressed that in the "old" way of developing energetic materials, the formulation team usually made decisions based on ballistic performance and mechanical properties but not on processability. Once a formulation was finalized, then the processing team would have to figure out how to design a process to produce a well-mixed and consistent product. With more advanced energetics ingredients (such as thermoplastic elastomer binders) and continuous processing methodologies (such as twin-screw extrusion), processability is in fact a very important concern. There is a strong need to consider processing along with performance during formulation. As such, rheology must be considered as one key parameter during the formulation phase. However, this concept does not seem to the norm in the industry to-date. It was commented that in the "self-managed product team" concept of the DOD world, formulating and processing could in fact be going hand-in-hand.

The discussion then turned to issues concerning rheological measurements. The question of accuracy versus reproducibility of viscosity drew some heated discussion. At the end, it was generally felt that for the purpose of process design and development, accuracy was essential. For quality control during operation, on the other hand, reproducibility was more important.

Due to the intense interest of many of the participants, the discussion went on for a little while even after the announcement that the mixer hour had started. The discussion probably could have lasted for another hour or two if time permitted. The group clearly did not have time to address many of the issues on the list itself. This is a strong indication that a similar open discussion forum on rheology should be encouraged for next year's meeting.

Eighth Annual Meeting
Continuous Mixer and Extruder Users' Group
Alexandria, VA
21-22 September 1995

Open Discussion
Feeder Accuracy Determination

The discussion was attended by approximately 20 participants. The group was lively, and the topic of discussion shifted rapidly. The spirit of the discussion was a brainstorm of current issues and concerns regarding feeding equipment which are summarized below. When known, the contributor is listed.

Early in the 1980s when continuous processing technology was being redefined, there were two areas of concern: feed rate reliability and on-line quality control. These are the same concerns that we have today.

The discussion was opened by Ernest Brown who recanted a feeder-related accident due to a surge of ammonium perchlorate in a co-kneader.

A poll was taken of participants as to which activity was using or considering vibratory feeders. Currently SNPE is the only organization using vibratory feeding. Eric Giraud described its implementation.

Bruce Lowden of K-Tron, who admittedly restrained himself from sales-oriented comments, made the point that our technical issues haven't changed due in part to the feeders we are using haven't changed. Many of us are using feeders and controllers from the 1970's and 1980's. He outlined the following advances in the technology:

- Advances in control algorithms/applications of statistical process control (SPC) which are implemented in the latest controllers.
- Improved data acquisition systems with better alarms.
- There are new hopper designs, such as a spherical bowl, which feature more screw exposure resulting in an increased screw fill.
- Signals are now serial instead of analog (even the load cell).
- Automation of start-up.
- Improved handling of refill–feeder can compensate for non-linear head effects.

Another participant made the point that it was critical to test the complete system–not just the isolated feeder but to include the piping.

Martin Gough stressed that it was important to characterize the ingredients analogous to rheological study.

There was some discussion as to alarm limits for shutdown. E. Giraud suggested a +0.4% deviation for 30 sec. Others expressed similar criteria. Mr. Giraud described aluminum doping experiments to study feed variations. SNPE's technique used three-second pulses of aluminum spaced one minute apart. The extrudate was analyzed to determine how the aluminum was dispersed by the process. He referenced work presented at the 1994 meeting at Marshall, TX.

Eighth Annual

Continuous Mixer and Extruder Users' Group Meeting

LESSONS LEARNED

Highly Fille[illegible]re

Stevens Institute of [illegible]
[illegible]
Hoboken [illegible]
201-2[illegible]
Fax: 201-216-5[illegible]

May 12, 1995

Mr. David Fair
Production Base Modernization Activity
Picatinny Arsenal, U.S. Army Base
Dover, NJ 07801

Dear Dave:

Here is a lesson learned in response to Morton's letter dated May 3, 1995. Let me know if you need further information.

Regards.

Dilhan M. Kalyon
Professor & Director

Title: Se[illegible] of powder feed according to density and

Program: Experimental and theoretical analyses for particle segregation and maximum packing value determination

Keywords: Segregation, particle size, feeding

Background: Propellants, explosives and pyrotechnics require blending of powders with different particle size distributions. If powder components with differing density or size are fed from same conduits/feeders segregation according to size or density can occur.

Lessons Learned: The greater the differences in density or size the greater is the segregation effect. Upon segregation the powder can fractionate to generate zones in hoppers, bins etc., with each zone exhibiting a maximum packing fraction which is less than the packing fraction of the homogeneous particle blend. This clearly presents safety + quality ramifications especially for highly filled materials. For more information, use Fiske, Railkar and Kalyon, "Effects of Segregation on the Packing of Spherical and Non-Spherical Particles", Powder Technology, 81, 57-64 (1994) or call Prof. Kalyon at (201) 216-5030.

ERATIONS

THIOKOL
SPACE • DEFENSE • FASTENING SYSTEMS

LOUISIANA PLANT
P.O. BOX 30058
SHREVEPORT, LA 71130-0058
(318) 636-5051

May 23, 1995

To: David Fair, PBMA

From: Advanced Engineering Manager, Thiokol

Subject: Lessons Learned about Feeders and Material Handling when Feeding a Twin Screw Extruder

In response to the questions posed concerning the above subject, Thiokol has had three major examples of "lessons learned" in handling materials in continuous processing. The three items are reported below in the format requested.

Title: Metal Powder Handling

Program or Product: Infrared Decoy Flares

Keywords: metal powders, deluge, water

Background: The twin-screw extruder facility at Longhorn is being used for processing infrared decoy flare composition. This composition is mainly magnesium powder (nominal 20 μ) and powdered polytetrafluoroethylene (PTFE) with a rubber binder dissolved in acetone. The facility has had a deluge system in operation for the entire time that it has been in operation. The magnesium feeder is located on a mezzanine over the extruder. Due to an apparent failure of one of the ultraviolet detectors, the deluge functioned one afternoon right at the end of a flare composition run. The equipment was not operating and no one was in the operating bays. When the deluge functioned, a quantity of water entered the loss-in-weight feeder and began reacting with the magnesium powder. Approximately 80 lb of magnesium was in the feeder hopper and approximately 240 lb was in a large live-bottom bin used for refill of the feeder hopper during extended runs. The reaction was proceeding vigorously with liberation of a large amount of hydrogen gas. The hopper was becoming very hot and there was concern that there could be an ignition that could propagate to the large hopper over the feeder. To reduce the reaction and cool the hopper, several gallons of diesel fuel were poured into the feeder hopper. This served to cool the hopper and coat some of the metal powder to slow the reaction. The hopper was allowed to stand overnight with ventilation running in the bay to prevent any hydrogen buildup. The next day the feeder was run into buckets to collect the

diesel and magnesium for transfer to the burning grounds. No damage was sustained by any of the equipment.

Lessons Learned: Following the incident, a review was held on the facility response in this case. It was determined that the deluge on the mezzanine was not appropriate since metal powder fires are aggravated by the addition of water. In this case, there was a hazardous situation created by the water when there had been no fire at all. The corrective action selected specifies that the deluge heads will be plugged when metal powders are being processed from the mezzanine. For operations not involving potential reactions of ingredients with water, the deluge heads will be active.

Title: Twin-Screw Feeder Gear Box

Program or Product: All

Keywords: Bearings, gear boxes, purging

Background: A twin-screw feeder was purchased from Control & Metering for use with the twin-screw extruder facility at Longhorn. The feeder has performed extremely well in feeding a variety of materials to the extruder. It has been found on disassembly that the seals at the rear of the hopper are not adequate to prevent migration of material into the drive area. Frequent disassembly and cleaning are required to keep this area free of contamination, especially when changing from one material to another in the feeder.

Lessons Learned: The main lesson here is to stress to vendors that modifications to their equipment must take into consideration many factors that they are not used to worrying about when they deal with explosives. Not only must explosion-proof electricals be specified, but pinch points and cracks and crevices must be eliminated.

Title: Conveyor Monitor

Program or Product: All

Keywords: motion detector, conveyor, stalling

Background: A conveyor system was installed to move material between pieces of processing equipment. The conveyor drive motor was monitored in the control room to determine when the conveyor was activated. This system was functioning through the control system with alarm monitoring for any stoppage of the motor. It was assumed that any conceivable overload on the conveyor would stall the electric motor and give an alarm. It was found that the conveyor belt jammed (during an inert run) and stopped moving but the electric motor kept turning and

gave no indication of a problem. When the stopped conveyor was noted, the system was immediately turned off and the problem was located and corrected.

Lessons Learned: From this experience, a positive indicator was added to detect the actual motion of the conveyor belt instead of relying on the electric motor performance for positive indication of the correct operation of the conveyor. Slippage of the drive on the belt permitted the belt to stop without the motor seeing an overload. An optical monitor was installed on one of the idler wheels under the conveyor belt to sense the loss of motion of the belt.

The above cited items are the only major problems identified in the continuous processing area for the twin-screw extruder facility concerning feeders and material handling.

If you have any questions concerning the above, please contact me at 903-679-2543.

Very truly yours,

David R. Dillehay

David R. Dillehay, PhD

and Metering

TELEFAX

FROM: [X] **CANADA**
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[ ] **USA**
1410 Kingsland Drive
Batavia, Illinois 60510
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To:	Mr. Dave Fair	From:	Andy Kovats
Company:	Picatinny Arsenal	Date:	May 30, 1995
Dept.:		Re.:	**LIW FEEDERS FOR TWIN SCREW EXTRUDERS**
City:	New Jersey		
Fax #:	(201) 724-2314		
Phone #:			

Dear Mr. Fair:

We are pleased to respond to the May 3rd letter of Mr. Morton Greene, requesting "Lessons Learned about Feeders and Material Handling when Feeding a Twin Screw Processor".

We have not submitted the information per the format requested, as this is perhaps more applicable to users of the equipment as a function of a specific program or product. Rather, as a Loss-in-Weight Feeder manufacturer, we are pleased to submit the list on the attached page as a summary of feedback we have received from end users. We trust this will be of value to the U.S. Army.

Please let me know if you require any more information.

Yours very truly,

CONTROL AND METERING LIMITED

Andy Kovats, P.E.
Energetics Sales Manager

LESSONS LEARNED ABOUT LOSS-IN-WEIGHT FEEDERS WHEN FEEDING A TWIN SCREW PROCESSOR

1) Scales should incorporate full mechanical counterbalancing of the dead weight (feeder and hopper), thus permitting the full load cell resolution to weigh material, not metal, thus improving performance;

2) Fulcrum for levering system should be frictionless and accessible;

3) Scale should be suspended (not platform) since, in addition to being more stable by definition (center of gravity below fulcrum), this design permits instant and easy access to critical scale components, thus decreasing downtime. Also, the heavy, explosion proof motors are much less likely to distort the scale.

4) While analog load cells may have their place in certain applications, load cell should be digital to increase resolution and eliminate analog drift;

5) Load cell should be low displacement design in order to stabilize quickly and return to gravimetric control within 3 - 5 seconds on completion of refill.

6) Twin concave, co-rotating fully intermeshing twin screws are the preferred feed mechanism for fine powder handling. In energetics applications, these are supplied with purged outboard bearings.

7) Fractional HP motors are not available rated for Group E. In certain cases, with customer approval, TENV motors with purging according to NFPA 496 can be supplied if required.

8) All welds are required to be continuous, ground smooth, and dye penetrant checked.

9) All gasketing to either be conductive or supplied with grounding straps.

10) Certain applications prohibit the use of all heavy and galvanized metals. Stainless steel and aluminum are acceptable.

GENCORP
AEROJET

Propulsion Division

Aerojet ramento → Yellow

Memo

To: J. B. Chambers

14 October 1992
JAC:5262:946

From: J. A. Campbell

Subject: A Summary of Lessons Learned at the Pilot Plant

Distribution: M. K. Wong, C. B. Stanley, G. A. Fluke, W. Wakamiya
L. A. Howell, M. L. Wirth, C. A. Cervenka, R. E. Thompson,
J. D. Robinson, File

A brief summary of lessons learned during the pilot plant experience is enclosed. Any questions regarding this submittal should be directed to the undersigned.

J. A. Campbell
Process Development
PMR&D

Approved:

Rovied 5/3/95

M. K. Wong, Manager
Process Development
Propulsion Materials R&D

LESSONS LEARNED AT THE CONTINUOUS MIX PILOT PLANT

12 October 1992

Process Development

Propulsion Materials Research and Development

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1. SUMMARY

This report provides a summary of all work conducted at the Continuous Mix Pilot Plant (CMPP) during FY-91 and FY-92. This work has been documented in numerous reports, and this report only serves to summarize the lessons learned from each of the subsystem and run tests in a single volume.

The pilot plant was designed to facilitate the successful activation of the Yellow Creek Continuous Mix plant by identifying and addressing process issues on a pilot plant scale, evaluating system parameters, supporting the development of a propellant suitable for continuous mixing, ensuring scale-up predictability, and providing direct training for engineers involved in conducting the Yellow Creek activation. The specific goals involved were designed to meet the requirements of various sections of the Loaded Segment Product Development Team Development Plan as shown in Attachment 3.0.

2. LESSONS LEARNED

2.1 Oxidizer Fluidization

2.1.1 Unground AP

A truly optimal fluidization system must provide steady, controllable transfer of a material without seriously affecting the properties of that material. In the case of unground AP, dilute phase transfer can cause significant attrition to the AP particle, and this is unacceptable because a reduction in AP particle size leads to a variation in propellant burn rate. The amount of attrition is increased by the velocity of the particles within the transport line, so any method useful in transferring the particles reliably at lower velocities is apt to reduce attrition.

Pilot plant work showed that long radius bends ($r \geq 15D$) and step changes in the oxidizer line reduced particle attrition, but that dilute phase fluidization in and of itself produced an unacceptable amount of attrition due to the velocities required to obtain dilute phase conditions. The pilot plant did achieve an acceptable degree of particle attrition, but only by

reducing the particle flow rate well below the dilute phase threshold into the transition region between dilute and dense phase flow. This compromise produces a very unsteady fluidization flow regime characterized by surging of AP through the line. To build a system functionally similar to that used at the pilot plant would require the installation of non-optimal equipment to produce a system susceptible to line plugging.

It is, therefore, recommended that any unground fluidization line used for feeding the unground metering system to the mixer should be built as a dense phase system and not as a dilute phase system as originally planned at the pilot plant. The dense phase system is designed to operate at low velocities and this will lead to improved processing without reducing product quality.

2.1.2 Ground AP Fluidization

Ground AP is not subject to the same attrition concerns associated with the larger AP particles and, therefore, fluidization parameters can be set based on processing constraints. This means that dilute phase fluidization of ground AP is practical and should be used at Yellow Creek. It would not be a good idea to attempt to use ground AP in a dense phase system due to its tendency to compact under pressure. Such behavior could easily lead to line plugging.

2.1.3 Hopper Design

The interior surfaces of the hoppers should be polished to a 32 RMS (#7) finish in order to reduce AP adhesion, retard corrosion, and enhance cleaning. The reduction in AP adhesion permits the construction of hopper bins with shallower hopper wall angles which could be beneficial at Yellow Creek. It is not recommended that Teflon or other bin coatings be used on the storage hoppers since the 32 RMS finish produces less wall friction with AP than Teflon or other bin coatings.

Any hopper used as a fluidization receiver should utilize a tangential entry with an inlet one-to-two sizes larger than the in coming fluidization line. This combination should reduce attrition significantly. In addition, the hopper should be fitted with a baffle located above the inlet to prevent direct path transport of fines into the gas filters.

.oppers designed for use with ungrou[illegible] .uid be designed to permit mass flow in order to permit first-in-first-out particle transfer. Flowfactor studies show that the minimum cone angle for unground AP mass flow is 70°. To account for any material consolidation within the hopper, it is recommended that a 75° angle be used for the unground AP hopper at hopper diameters smaller than three feet. To conserve headroom, a 75° hopper angle may be used at the discharge area, then reduced to a 65° angle when the hopper inside diameter exceeds three feet. The hopper outlet should be sized to facilitate refill of the LIW feeders, but it will require a 6" or larger opening to ensure that mass flow is obtained. If mass flow is not obtained, the particles will segregate within the hopper, and this, in turn, will lead to variation of the in-line burning rate.

The ground AP hopper must be designed somewhat differently due to ground AP's ability to gain strength rapidly with time. A mass flow hopper can not be constructed for ground AP. Fortunately, ground AP does not require a mass flow hopper since particle segregation is not apt to lead to changes in propellant properties. It is therefore recommended that ground AP hoppers be constructed with a live bottom bin having a minimum inlet diameter of six feet.

Additional flow aids are recommended for ground AP. These include aeration pads and mechanical agitators. In addition, movement of the ground AP is very important. It should not be left in a receiving hopper for a significant period of time and should not be vibrated unless being discharged. It should be noted that the combination of oxidizer and stress are very damaging to a hopper. Proper welding techniques must be used to prevent embrittlement of the stainless steel. If this is not done, the chlorine in the AP will significantly weaken the metal to the point that the use of agitators or other flow aids could lead to the cracking of the hopper.

2.1.4 Rotary Valve Equipment

Rotary valves are used as metering devices from hoppers to either fluidization lines or Loss-in-Weight (LIW) feeders. These valves are a very important part of any fluidization operation. The following paragraphs outline lessons learned at the pilot plant in regards to rotary valves:

Rotary valves must act as sealing sur[illegible] a fluidization system. However, the valve and valve body are normally constructed of stainless steel and improper setting of the valve can lead to metal-to-metal contact. In order to avoid this problem, Teflon wiper blades were used with some success at the pilot plant. These blades should extend beyond the side edge of the vane to prevent metal-to-metal contact.

2. Rotary valves have numerous vanes. The more vanes used, the more uniform the feed to the fluidizing line. A minimum of six vanes should be used at Yellow Creek, but eight or more would represent a substantial improvement.

3. Pressure transducers should be installed on either side of the rotary valve in order to measure the pressure drop across the valve. If this value changes significantly, it could indicate that the Teflon wipers require replacement.

4. When a rotary valve drops AP into a feed stream, the vane becomes filled with pressurized gas. It is necessary to vent this gas prior to the vane's refill or the gas will interfere with the filling of the vane during its next pass. The vent line normally runs back into the top of the fluidizer hopper to reduce the amount of AP fines lost in the operation. At the pilot plant, the ground AP receiver hopper was too small and occasionally the hopper would become filled with ground AP. When this occurred, the vented nitrogen would blow directly on top of the ground AP causing the entrainment of fines in the hopper's venting system.

5. All solid receiving hoppers require a means for venting gas (this includes the LIW feeder hoppers). If a suitable path is not made for the solid displaced gas in the hopper, it will find a path either through the feed port, exit port, or relief system. This vent should be set up with a nuisance dust collector of sufficient capacity to prevent the release of fine AP to the environment.

6. The rotary valve must have variable speed control to cover the range of material to air ratios anticipated for service (3:1 to 10:1).

7. The rotary valve vanes generally do not deposit an entire vane volume of oxidizer per revolution. The pilot plant experienced about a 20 % fill efficiency and the rotary valve should be sized accordingly.

8. AP is a relatively safe propellant ingredient until exposed to metallic dust, oil, grease, or other finely divided fuel component. Since rotary valves require lubrication, it is possible that the AP could become contaminated with oil or grease during normal operations. To mitigate this risk factor, it is recommended that halocarbon grease and lubricating oil be used with rotary valves (and all other equipment requiring lubrication which may be exposed to AP). Since this material is expensive and hard to procure, it would be best to order equipment with standard lubrication and have Yellow Creek maintenance replace the lubrication prior to use of the equipment with AP.

2.1.5 Fluidizing Line

The fluidizing line is the piping that extends from the fluidizer to the receiver hopper. The following paragraphs summarize the pilot plant experience with these lines:

1. Only flush mounted pressure transducers should be used in the fluidization line because of the tendency for solids to build up in cavities. The buildup not only influences the data obtained, but could lead to increased corrosion at these areas.

2. Severe rusting has been observed on all stainless steel surfaces coming in contact with AP. This is particularly important in regards to the fluidization line because it is generally harder to clean than other items of equipment. In order to minimize problems, eliminate moisture from the lines to the largest extent possible. Prevent AP from sitting in the lines for long periods of times by frequently blowing the system out. Install piping that has been welded properly. Finally, install the pipe lines such that they can be inspected regularly and cleaned. If the pipe lines are installed in an inaccessible location, the difficulties encountered in reaching these lines will prevent the regular maintenance required to keep them clean.

3. Occasionally run an abrasive material through the conveying lines to remove the AP buildup on the inside walls. Water can be used for cleaning only if the system is thoroughly dried after cleaning. Any pools of moisture will dissolve the AP permitting it to enter cracks and crevices. AP solutions in water are much more corrosive than dry powder AP.

2.1.6 Welding Requirements

Installation of an oxidizer fluidization system requires the welding of pipe and hoppers. The material of preference is 304 L (low carbon) stainless steel. Welding techniques should be used that will minimize the chlorine embrittlement which led to the hopper cracks responsible for cancelling run CMPP-025E. Welds must be smooth and be readily cleaned. Grinding wheels and brushes used during welding must be compatible with these requirements or rusting will occur in the area of the ground down weld. The specific welding requirements for oxidizer service called out in various specifications must be rigidly adhered to or premature cracking and corrosion will result.

2.1.7 Control

The pilot plant was set up with a single control system for the two fluidization devices. This was found to be impractical due to the significant differences between the materials being conveyed. Therefore, each fluidization system should be completely separate from all others. This is particularly important in regards to gas pressure control.

In addition, most pieces of equipment require purges during operation. Pilot plant experience has shown that these purges are often overlooked by operators (either being left off or ignored when a plug or other difficulty develops). These purges should, if possible, be set to alarms that will alert the operator when flow to the purge has been halted.

2.2 Oxidizer Metering

2.2.1 Overview of LIW Feeders

Oxidizer feeders should be viewed expansively since their accuracy is influenced by the environment in which they operate. The

feeders used at the pilot plant operate on the principle of loss-in-weight (LIW) such that the feeder and its hopper contents are weighed and compared to previous readings. The difference in weight for a given time is the feed rate. In order to adjust the feed rate, the feed screw or screws are turned either slower or faster to make the measured feed rate change match the set point entered by the operator. This type of feeder must change its mode of operation when refilled since the addition of material to the hopper would necessarily disrupt the normal gravimetric algorithm noted above. Therefore, during refills, the feeder is placed in some type of volumetric control. This control can be as simple as holding the screw speed constant at the screw speed last used in gravimetric mode or be complicated by vendor supplied "refill algorithms" that utilize past screw speeds as a function of total hopper weight to vary the screw speed during refill. Regardless, the LIW feeder's weakness is the volumetric period and this period should be minimized.

2.2.2 LIW Feeder Control

The most important point in proper LIW feeder control is uniformity. The best possible results will be achieved if the screw speed never has to change at all. In order to approximate this, it would be necessary for the material being metered to have a constant bulk density because any change in density will be reflected in changes in screw speed. In addition, the material must be capable of flowing readily. If the material tends to bridge, the feed screws will be starved. If the material sticks to the feed screws, the amount of fill on the screws will vary with time. It is obvious from these requirements that the LIW feeder works best when used with a material that behaves like a liquid. Therefore, the design must be based on the material to be fed and every attempt to improve the flow of that material should be made.

In the case of the pilot plant, the most difficult material to meter is the ground AP. This material does not flow well having a tendency to stick to surfaces and to bridge. In addition, its bulk density can change significantly with time since it is also subject to compaction. For a material such as ground AP it becomes necessary to add flow aids to try to improve transfer. A vertical agitator in the LIW feeder hopper is essential for preventing ground AP from bridging in the hopper and, therefore, starving the feed screw. Without the

vertical agitator, the material will [illegible] ed properly. Twin concave screws have been found to satisfactorily meter the ground AP out of the feeder by preventing buildup and caking along the discharge spout.

The manner in which the feeder is refilled can be extremely important in obtaining reliable feeding. In general, it is best to refill frequently for short durations. This tends to leave a sizable heel of material within the hopper and this has two major advantages: First, the small quantity added to the hopper exerts less force on the material immediately above the screw leading to smaller changes in bulk density during refill, and, second, the time that the unit is in refill is relatively short. The former point is extremely important since any change in the density of the material during the refill will be passed along as an error in delivery rate during volumetric feeding.

While the spacing of refills is important, the mode of refill is also important. If the refill is metered to the LIW feeder, the refill will tend to be somewhat repeatable. As noted above, this is very important because a change in refill time can disrupt the volumetric efficiency of the feeder. For instance, if the refill occurs very fast, the impact of the added oxidizer will be severe causing compression of the oxidizer already in the hopper as well as disruption of the weigh elements (this normally will cause the volumetric mode to continue for a longer time until stability is again achieved). If the refill is very slow, the relative time that the unit is in gravimetric mode decreases with respect to the less accurate volumetic mode. Of the two problems, the first is most severe and the use of a rotary valve makes a dramatic difference in the consistency of the refill.

A problem that often is overlooked in setting up a LIW feeder is the discharge point of displaced gas. Whenever a gas filled chamber is filled with solids, the gas must be displaced. This gas can flow through a properly sized vent, back up into the feeding hopper, or down through the feed screw. In order to prevent the latter two problems, the refill must be controlled such that the vent is capable of handling the displaced gas without pressurizing the hopper. In addition, the use of a significant heel within the LIW feeder is important to prevent the pressurized gas from "seeing" a path of least resistance through the screw flights. If this occurs, the AP will be fluidized through the feed screw into the downstream equipment. This will cause significant overfills during the actual refill period. Note that screw speed

becomes academic under [illegible] [illegible]tions since the prime moving force [illegible] nothing to do with the actual screw speed. The use of twin screws reduces the possibility of this type of problem, but does not eliminate it. However, a good vent system and significant heal will prevent this from occurring. It should be noted that a specific weight of material in the LIW feeder hopper does not in and of itself ensure that a sufficient heel is present. The heel is the volume of AP between the screw flights and the top surface of the AP at its shortest point. If agitation is not sufficient to maintain a level AP surface, the fact that feed screws tend to take material from the drive side of the flights first will tend to cause ratholing in the rear of the hopper. These ratholes provide excellent air paths for the release of pressurized gas.

A refill problem somewhat related to the volumetric difficulties mentioned above has been shown to occur after the refill has been completed. This problem occurs when a rotary valve either leaks, holds up material which eventually falls back into the LIW feeder, or exposes a vane which, due to its angle, drains out so slowly that the LIW feeder returns to gravimetric control prior to the complete discharge of the vane. This behavior invariably leads to increases in LIW feeder discharge and generally can be identified with higher screw speeds immediately following the volumetric period. The increases are caused by the gravimetric algorithm which compares the current weight to a past weight to determine the screw setting. When material dribbles into the LIW feeder the rate obtained is the set point plus the dribble. The pilot plant problem was mitigated (but not eliminated) by reversing the rotary valves one quarter turn after refill. It is recommended that a positive means of shut off be installed immediately below the metering valve at Yellow Creek to stop any dribble during the gravimetric period.

Throughout this discussion, it has been assumed that no flow difficulties would occur above the rotary valve. This assumption is probably not warranted based on pilot plant experience. However, unlike the LIW feeder which cannot withstand vibrations (and must, in fact, be installed on a stand separate from all walk areas or other equipment stands), the hoppers located above the LIW feeder may be vibrated with great vigor. This vibration must only occur during actual material movement or it could lead to the compaction of the ground AP. Impact vibrators, live bottom bins or aeration pads can be used to help supply the rotary valve with a constant supply of ground AP during refill. Unground AP requires less vibration than

ground AP, but some typ[illegible]w aid should be provided for the coarse material as well. The pilot plant used pulsed high amplitude, low frequency impact vibrators for the unground AP hopper and continuous low amplitude, medium frequency vibrators on the ground AP hopper.

2.2.3 Non-Fluidized Oxidizer Conveying

The following comments are directly applicable to screw conveyors, but some of the comments are applicable to other oxidizer equipment.

2.2.3.1 Screw Conveyors

1. Ground AP produces a significant amount of airborne dust. This material influences all device seals whether static (e.g., conveyor lid seals) or rotary (e.g., shaft seals). The pilot plant experienced significant leaking at the ends of the conveyor lids where they overlap with the inlet flanges. This problem can probably be eliminated by the use of cross supports to eliminate any overlapping of metal pieces. It would be possible to eliminate this problem by sealing the lid permanently, but this is not recommended since accessibility to the interior of the conveyor is extremely important for cleaning and inspection. No difficulties have been encountered with the screw conveyor rotary seals since they were replaced with Meco Woodex HD seals with glass filled Teflon rotors and stainless steel stators.

2. Buildup of ground AP within the screw conveyor has been noted at the pilot plant. The buildup tends to be most severe within the open space located in the upper part of the U-trough conveyor, but some buildup was also noted on the screw itself. The use of shroud covers to fill in the open space above the screw may minimize this problem. Such a device would offer the advantages of the trough conveyor with its ease of cleaning and inspection and the tubular conveyor with its minimum of material accumulation.

3. Conveyors, and in fact all equipment, should be installed with maintenance access to the device. The conveyors and feeders

used at the pilot p[illegible] required significant maintenance a[illegible] could have been acc[illegible]ned more effectively with enhanced acc[illegible]ne installed devices.

4. Conveyors can be operated at a wide variety of speeds. The pilot plant has shown that a variable speed drive is useful. For Yellow Creek's conveyors, the drives should permit operation in the range of 10 to 100 rpm. This range of speeds will cause virtually no particle attrition (if the trough is designed with similar clearances to the device used at the pilot plant) and will produce acceptable transfer of the AP to the continuous mixer.

5. The use of Teflon shoes at the midpoint of all conveyors is recommended to prevent the possibility of screw deflection leading to metal-to-metal contact. In addition, Yellow Creek should not use the cross conveyor system used at the pilot plant because the distance between bearings in the Yellow Creek plant would require the use of hangar bearings. Currently, no acceptable hangar bearing design for use with AP has been located. Two separate conveyors stacked at the mixer inlet would provide an acceptable system without the use of hangar bearings.

6. AP gradually builds up a glaze on any surface it slides across. This glaze can become thick and hard enough to disrupt a LIW feed screw, or it can simply coat a surface and give that surface a new coefficient of friction which will eventually lead to significant AP buildup. Currently, rigorous cleaning of the system is the only method available for eliminating this problem. However, given the length of the proposed runs, the glaze could still be an important factor even after cleaning the surfaces.

2.2.3.2 Diverter Screw

The diverter screw has been a constant source of trouble at the pilot plant. The main problem associated with the diverter screw is the fact that its interior sleeve must slide back and forth through an external housing. The space between the sleeves tends to buildup oxidizer dust which gradually increases the amount of force required to move the interior sleeve until the sleeve can no longer be moved by the nitrogen driven piston located on top of the unit. Cleaning eliminates the problem,

but use of the scre[illegible]es renewed fouling and eventual failure. [illegible]ot recommended that the pilot plant design be used without modification at Yellow Creek.

2.3 Premix Metering

Premix metering has been one of the more trouble free subsystems evaluated at the pilot plant. Both the Moyno progressive cavity and Waukesha lobe pumps have handled their respective recirculation and metering assignments well. None-the-less, certain information has been learned during the pilot plant trials.

2.3.1 Pumping and Piping Observations for Premix

Premix can be metered with great accuracy using volumetric feeding. It has been determined that the pump speed, which can be closely controlled if the tachometer is attached to the motor, is by far the most significant flow rate variable. A secondary variable is the pressure across the metering pump. Although changes in the pressure across the pump head do lead to variations in the premix flow rate, these variations were eliminated at the pilot plant by fitting the recirculation system with a control valve capable of increasing the metering pump's inlet pressure to match the pump's outlet pressure and, thus, producing a zero pressure differential across the pump head. The fluid temperature at the pump is a third factor influencing flow rate, but it was determined that temperature changes of five degrees or less make little difference in the premix delivery rate, and it is believed that control to this degree should be attainable at Yellow Creek.

Metering reliability can be detrimentally affected by restricting flow to the metering pump. This situation has not occurred in the modified pilot plant, but did occur in the proposal stage pilot plant. The modified pilot plant has shown that the premix system is capable of running in excess of ten days with no change in performance. This is believed to be due to the constant movement of the premix accomplished by tank agitation, the recirculation pump, and a vibrating filter at the discharge to the Moyno pump. Since the positive displacement pumps used are capable of maintaining flow even in restricted lines, aluminum settling downstream from these pumps is not apt to be a problem unless the line becomes

completely p However, at the inlet to the recircu , the total transfer head available can not be increased to overcome setting and it is necessary to design the inlet piping as short and free of bends and crevices as possible. The progressive cavity pump does not require a strainer and it is not recommended that one be placed between the tank and the recirculation pump because the strainer will eventually fill and restrict flow to the pumping system.

Unlike the progressive cavity recirculation pump, the Waukesha lobe pump does require some protection from large particles or agglomerates. The filter system used at the pilot plant uses a Rosedale vibrating filter designed for use in the auto painting industry to remove large agglomerates from a slurried material. This filter system is located between the recirculation and metering pump in order to permit an increase in pressure as the filter gradually fills up. In all tests to date, no significant buildup on the filter has been noted and this is believed to be due to the type of aluminum used in the premix as well as the vibrating nature of the filter.

With the use of a slurry material, shaft sealing can be difficult. The Waukesha pump uses an O-ring seal, while the Moyno pump uses a mechanical seal. The Moyno seal has experienced some difficulties, but most of these could have been avoided by proper installation of the seal. It is particularly important to not over tighten the seal as this could damage the sealing surface. In addition, the seal should be pressurized with DOA according to the manufacture's recommendations to prevent aluminum from degrading the seal surfaces. If a seal is properly installed and still appears to be leaking, it may be worthwhile to lap the seal face to remove any possible surface imperfections.

The cleaning of the premix system is very important due to the tendency for aluminum to settle in the lines. Pilot plant experience has shown that draining the lines removes most of the material, but to obtain acceptably cleaned lines requires the use of pigging. The pilot plant utilized rubber stoppers for this operation. A semi-automatic pigging system concept should be investigated for use at Yellow Creek.

2.3.2 Premix System Start-up

In starting the premix system, particularly when the system has previously been used without cleaning (e.g., after an unexpected shutdown),

it is impo[illegible] to remember that the available flow area [illegible] pipe lines may be only a small fraction of what it is in the steady state lines. This means that a lower flow rate will actually require a higher pump discharge pressure. Therefore, when starting up, the system should be brought up to the target flow rate relatively slowly based on pump discharge pressure. The pressure should never be allowed to exceed either pump's relief valve capability or fouling of the mechanism may occur which could cause leakage of premix through the valve which would effectively invalidate earlier calibration work.

2.3.3 Premix Feed to the Mixer

The premix feed to the mixer should be kept as short as possible from the recirculating three-way valve. However, the pilot plant line drops over ten feet from the recirculating pipe line network without adversely affecting the performance of the metering system. The pipe drop would, if permitted to, result in the draining of the line after each diversion from feed. This type of behavior will affect start-up because a pool of premix rich propellant will invariably be followed with a premix poor, dry propellant. This problem was rectified at the pilot plant by the installation of a pinch valve immediately above the premix port opening. The pinch valve is controlled to stay closed whenever the system is in divert and to open whenever the system is placed in feed. This valve basically maintains a static head of premix within the drop section. This system has been used at the pilot plant with a great deal of success. However, it should be noted that aluminum will gradually settle out of the suspension and this could lead to plugging of the inlet valve or a period of aluminum rich feeding followed by polymer rich feeding. Times less than an hour or two should not, with this premix formulation, be a significant problem. Longer times will require drainage of the line prior to re-start.

2.3.4 Calibration

A continuous reading scale and PC computer provided an exceptional data collection and analysis tool. Attention to the scale precision/accuracy and timing requirements can provide virtually real time calibration of the feed system.

2.4 Fuel Metering

The final fuel metering system consists of two separate systems. One system uses a single Zenith pump, while the other system uses dual Zenith pumps in order to maintain a zero pressure differential across the metering pump. Both systems have been found to be extremely precise.

2.4.1 Pumping and Piping Observations

1. The pilot plant system uses the volumetric feeding of two final fuel streams. Results obtained indicate that volumetric feeding is quite acceptable and gravimetric feeding should not be required. The primary drivers behind metering accuracy are pump speed, pressure differential, and temperature, but the pilot plant's extremely low pressure drops between the mixer and the metering pump make the use of a dual pump system unnecessary. If pressures in excess of 25 psig are required, the dual pump system may be useful since the higher the pressure differential across the pump, the more likely it is that the pump will experience slip resulting in a reduced metering rate. However, the fact that slip is present does not necessarily mean that a metering problem will develop. The real metering problem will occur when the discharge pressure varies significantly in combination with slip because this will lead to differing flow rates than those achieved during calibration. Like the premix, the temperature sensitivity of the system is relatively small and temperature control of ± 5 °F should be satisfactory.

2. At the pilot plant, the discharge pressure of the final fuel actually dropped below atmospheric at the elbow located at the top of the ten-to-twelve foot drop to the mixer. While the fittings were successful in preventing final fuel from leaking out, they were not successful in keeping air out and air bubbles were entrained in the feed stream during feeding. This behavior will not affect the average flow rate, but it will adversely affect the system's repeatability. In order to eliminate this problem, a back pressure valve was installed on the final fuel line just above the mixer. This device was set to ensure that no portion of the final fuel line would ever drop below atmospheric pressure. The device was also useful in maintaining a constant

p[illegible] [illegible]arge pressure which is particularly [illegible] [illegible]or the single pump system.

3. The Zenith pumps used at the pilot plant are not suitable for use with solids. This means that a fine strainer should be installed on the suction side of the pump in order to remove any particles which may originate from the fluid or which may have flaked off from within the recirculation system. White crystals of urea have been found in the strainer during disassembly.

4. While unseeded Final Fuel 2 will not solidify at temperatures as low as 40 °F, the presence of seed crystals can cause crystallization at temperatures below about 65 °F. Since it is likely that some seed crystals will be present somewhere in the feed system, the final fuel system must be maintained above 75 °F. It is important that the entire system is maintained at this temperature because even a small portion of the line maintained at a lower temperature could cause crystallization along the wall leading to plugging within the fuel system.

5. The primary means for verifying the operation of the final fuel system remains the calibration. The calibration is an excellent method for accessing system health because a significant change in the pump displacement is a good indication of a metering system problem. The use of a continuous reading scale and PC computer can produce acceptable data if proper attention is given to the scale's precision, accuracy and timing requirements. However, due to the small quantities being measured, some care should be given to the location and environment of the scale as well. At the pilot plant, an enclosed box was required to prevent air currents from influencing the results. In addition, stand vibrations will also reduce the reliability of the data generated.

Using calibration as the tool of choice for verifying the system's reliability is complicated by the fact that it cannot detect problems occurring during the run itself. In order to ensure system reliability, it is necessary to install a flow sensor in the final fuel lines. The pilot plant has used two such sensors with good success. These devices should be used to obtain a flow reading at the time of calibration. The flow rate obtained should

ary significantly throughout the run. [illegible], the final fuel system may be experiencing some type of metering problem.

2.4.2 Clean-up of Final Fuel System

The final fuel system is particularly sensitive to fouling and a rigorous clean-up procedure is required to ensure system reliability. The pilot plant has found that DOA heated to between 100 and 120°F provides a good system rinse, but the rinse must be completed at least twice after draining to remove all final fuel. The system should be filled with DOA during shut-down periods to fully remove all air from the system and to dilute any final fuel that may still be within the pipelines. Pressure transducers and other elements that must enter the line should be constructed as flush to the pipeline as possible to prevent any stagnant areas within the line. Prior to re-using the system, the DOA should be first drained out of the system and then the entire system should be blown out with nitrogen gas to remove as much DOA as possible. The final fuel should then be flushed through the system with the first material being discarded unless lab testing shows it to be free of excessive amounts of DOA.

The pressure relief system on the final fuel system represents one area where the buildup of stagnant fluid will be unavoidable. The relief system can either be part of the pump body itself or be a separate auxiliary valve. At the pilot plant, auxiliary valves are used. These devices are necessary to prevent the gear pumps from generating excessive pressure due to some type of line plug (e.g., a downstream valve being closed). They operate by dumping high pressure fluid from the discharge side of the pump back to either the suction side of the pump or a reservoir. These devices must be disassembled and cleaned after every run. If they are not cleaned properly, final fuel will solidify within the valve seat area with the following consequences: the valve will freeze or be blocked shut and will not be able to relieve pressure as required leading to possible system damage, or the valve will become blocked partially open permitting the flow of fluid through the valve during the run. The latter problem will reduce the flow rate of IPDI to the mixer and could seriously affect the propellant's mechanical properties even if the pump was calibrated with the leak. This is due to the fact that the pressure may vary during the run, causing the amount of fluid flow through

.e leaking valve to increase (i.e., the effe. ..p of the pump could be increased).

2.4.3 Tooth Location

The final fuel systems used at the pilot plant have introduced their contents into the mixer in several ways: mixed together in a single final fuel stream, metered in two separate streams but recombined at the mixer tooth, and metered in two separate streams through two separate, adjacent mixer teeth. None of these changes appeared to alter the final propellant properties. However, at the conclusion to run CMPP-027, the clean-up revealed a hard donut of propellant around the mixer shaft in the vicinity of the second final fuel tooth. This behavior has been seen in past Polaris work and apparently results from the placement of the final fuel teeth. Based on the observations made to date, the movement of one or both final fuel teeth is probably possible. How far or where these teeth should be placed to eliminate the propellant cure around the shaft has not been determined.

2.4.4 Storage

The final fuel should be stored under an inert atmosphere (nitrogen is used at the pilot plant) at 80 °F. Agitation is not required for the IPDI unless there is a desire to enhance heat transfer. Agitation is probably a good idea for long term storage of Final Fuel 2. During storage, the final fuels should not be left in the process lines – there is a small but real possibility that the final fuel will come into contact with air. If the material is not moving, even a small amount of moisture could result in the formation of a plug of urea. If the material continues to move, the line pressure will be greater than atmospheric at most points and any leaks will be outward preventing air contamination. In addition, the recirculation of the final fuel will permit dilution effects to reduce the seriousness of contamination, and the filter to remove small, manageable crystals.

2.5 Continuous Mixer

The UK-150 mixer used at the pilot plant has been probably the most trouble free piece of major equipment at the pilot plant. The following paragraphs discuss observations made in the course of the pilot plant work.

2.5.1 Mixer Screw Speed

The mixer screw speed significantly affects the quality of the mixed propellant. It has been found that low temperature mixes (120°F outlet propellant temperature) can not be processed at 1371 lb/hr at speeds below about 70 rpm. The first sign of poor mixing is variability in propellant consistency. Generally, the propellant will first become very thin (similar to premix) and then grow increasingly dry until the material leaving the mixer appears powder like. Since the mixer is closed during all mixer operations, the mechanism behind the poor mixing can only be speculated upon. However, based on examinations of the mixer after a run and of propellant during a dry period, it is believed that low mixer speeds provide insufficient shear to fully incorporate the formulation's AP. This AP is forced to the barrel section of the mixer where it gradually builds a cake between the mixing teeth. At some point, these unstable cakes break off and are conveyed out of the mixer. The propellant itself takes on a sculpted look. In run CMPP-027, several periods of dry propellant were noted. These were probably due to clods of oxidizer breaking off from the vibratory trough, but it is also possible that this dry propellant is an indication of insufficient mixer speed which permitted AP rich propellant to buildup very gradually along the barrel walls before breaking off periodically to cause increases in the viscosity of the propellant.

2.5.2 Mixer Temperature

The mixer temperature was found to have a significant affect on the propellant's mechanical properties. In addition, the warmer propellant appears to improve propellant flow through the surge pot and Rotofeed inlet valve as might be expected. It was found that controlling the temperature based on the final mixer tooth prior to propellant discharge provided stable temperature control throughout the mixer with the possible exception of the oxidizer section. The latter difficulty is believed to be due primarily to the poor heat transfer contact provided by the mixer tooth in the mixer's powder region. Two problems are associated with controlling the temperature off a mixer tooth: First, the jacket temperature will tend to become too hot if flow through the mixer stops, and, second, the tooth temperature is probably not the actual propellant temperature. In order to avoid the first problem, the hot

water system's inlet valve was s[illegible] n conjunction with the mixer regardless of the tooth reading and then re-opened only when the mixer was re-started. The second problem is not serious, but it does mean that the 145 °F temperature used at the pilot plant may vary a small amount from the temperature required to obtain similar propellant properties at Yellow Creek. Once a temperature is selected, it can be controlled in a fairly reproducible manner. It is recommended that the propellant at the mixer outlet tooth be maintained at 145 °F to obtain satisfactory mechanical properties.

2.5.3 Hydraulic System Control

During run CMPP-024, a bird collided with a plant transformer shutting off power to the facility. The pilot plant's control system sensed this power failure and, as designed, automatically opened the mixer. This effectively ended the run. It is recommended that a back-up power supply be made available for opening the mixer shells in the event of an emergency so that the system will not be forced to open the shells without an actual out of limit thermocouple reading. Storage of sufficient pressure in an accumulator may be an alternative to the UPS system, but the pilot plant's hydraulic system has never been able to reliably hold a charge for long periods of time.

2.5.4 Mixer Clearances

After run CMPP-026, scratches were noted on one full row of mixer teeth and one full row of interrupted flights. It was found that when the particular row of flights in question were lined up in a specific manner, the opening of the barrels would result in contact of the flights with a row of mixer teeth. It was further determined that this occurred despite the fact that satisfactory clearances were available when the mixer barrels were closed. It is recommended that the Yellow Creek mixer should have its clearances checked at the full closed barrel position as well as at all intermediate positions between closed and open. The particular reason for the contact was never fully determined, but it is believed to be a combination of the machine's shaft being slightly lower with respect to the barrel than called for in the drawings (a manufacturing defect), play in the shaft and barrel sections due to age, and the higher temperatures currently being used. The high temperatures cause the screw to expand to a greater degree than the barrel sections and this caused the flights to move closer to the teeth.

2.5.5 Mixer Start-up

Mixer start-up at the pilot plant has been conducted in two ways: when the mixer is fully empty and when the mixer is full. In the first case, the start-up involves a line-out period where the premix is turned on first, then both final fuels, and finally the oxidizer. This leads to very thin material for about one-to-three minutes followed by progressively thicker material as time goes on. The line-out period at the pilot plant lasts for ten minutes. In starting the mixer with the mixer full of propellant, the mixer is first started and as soon as it reaches operating speed all four feed streams are diverted to the mixer. The time between mixer start-up and feed stream diversion is between ten and fifteen seconds. While these methods for start-up have worked satisfactorily, it is believed that a better process could be obtained by basing the start-up times on the actual times required for a diverted stream to truly begin to feed the mixer. Improvement in this area would improve propellant consistency and Rotofeed performance.

2.5.6 Mixer and Rotofeed Seals

The mixer seal system varies little from the Rotofeed or propellant pump seal systems. It consists of a separate air driven piston diaphragm pump for each seal. The pump transfers DOA to the seal region. Pressure at the seal is maintained by the seal itself and a back pressure valve set at about one to three psig. The DOA flows either through the valve or into the seal. A pressure switch is located on the line to indicate whether the seal pressure is being maintained. If the seal pressure is not being maintained, it is probably due either to a pump failure, a back pressure valve failure, or a seal failure. Difficulties encountered with the mixer system have generally been due to valve failures caused by debris fouling the relief valve seat which, in turn, prevents the valve from closing down properly. The use of back pressure valves rather than standard relief valves has provided more reliable pressure control since they are less apt to be affected by fouling. In addition, Buna N or nitrile seals tend to degrade at high temperature in the presence of DOA causing flakes which can foul the relief valve. Replacement of these seals with Viton or other more compatible materials can reduce the amount of flaking and make valve fouling less likely to occur. Two methods not attempted at the pilot plant, but which may improve system reliability,

involve raising the seal [illegible] permit the use of more robust valve[illegible] setting up a recirculating seal system.

2.5.7 Cleaning

Rice hulls were passed through the UK-150 mixer at the conclusion of run CMPP-026 (inert run). After several minutes of operation, the mixer was stopped and opened to reveal a highly polished barrel and screw fully free of propellant. Residual rice hulls and salt were easily removed from the mixer. Although rice hulls were unable to pass through either the Rotofeed or the propellant pump, the mixer screw was successful in moving the material to the discharge port where, unlike the other devices, gravity assisted in the removal of both the propellant and rice hulls without causing any backup in the mixer. If rice hulls are to be used in future work it is recommended that all pressure transducers be removed from the mixer prior to cleaning to prevent the scratching of the pressure transducer face and that combinations of rice hulls and ASRM propellant be safety tested to ensure that no particular combination of these ingredients is more dangerous than the neat propellant.

2.6 Surge Pot/Rotofeed Deaerator

The Rotofeed deaerator system was the source of serious difficulties during the months immediately following the activation of the pilot plant. These difficulties were largely remedied by the use of thorough subsystem testing of the deaerator. While the following paragraphs discuss lessons learned based on these tests, perhaps the biggest lesson learned is that thorough subsystem testing is a highly beneficial exercise for improving operational efficiency which will repay the extra time required many times over.

2.6.1 Surge Pot

The pilot plant surge pot has been shown to be somewhat undersized for the task required. During steady state periods, the capacity is quite adequate. However, during Rotofeed feeding difficulties which are quite common at start-up, overflow of the surge pot has occurred. This problem can be mitigated by producing propellant of uniform viscosity,

running the Rotofeed s[illegible] above its flooding point, and operat[illegible] low level within the surge pot. The viscosity is influenced primarily by the mixer and not the surge pot. In fact, while the surge pot should be jacketed, the temperature should be set to maintain the mixer temperature, not to either cool or heat the propellant. The lower level can best be achieved by supplying the operator with a good view of the surge pot contents. The camera located above the surge pot is the most important pilot plant camera, and it is highly recommended that the Yellow Creek facility install a similar high contrast device under their mixer.

Because of the occasional overflows noted, the surge pot and any other instruments, pipes, or equipment pieces located below the surge pot should be designed to be both easily cleaned and propellant compatible. This design should also avoid surfaces that may hold up propellant and influence the surge pot weight. For example, the pilot plant surge pot has wheels and water jacket connections which have been difficult to clean once contaminated.

In addition to spillage out of the surge pot, some thought should be given to preventing items from falling into the surge pot. At the pilot plant a cotton shroud is attached to the mixer discharge port. The shroud forms a tent around the surge pot to prevent items from outside the mixer from inadvertently dropping into the pot. This is very important since the surge pot is upstream of both the Rotofeed and propellant pump.

2.6.2 Rotofeed Inlet Valve

The Rotofeed inlet valve controls the pressure drop between the surge pot and the Rotofeed and, in so doing, controls the flow rate of propellant into the Rotofeed. Observations made during pilot plant work indicate that the primary cause for fluctuations at the discharge of the Rotofeed is the fluctuation of propellant through the inlet valve. Some of this fluctuation is due to valve control. However, it appears that much of the variation is due to changes in material consistency. The valve can be maintained within ± 2 % of its setpoint during most steady state periods. Occasionally the propellant consistency will change enough to require significantly more valve movement. While it may be possible to size a valve to produce slightly better control over the steady state portion of the run, it is impossible for a valve to control accurately over the entire range of

consistencies experienced during pilot plant runs and this should not be attempted. Likewise, the pilot plant demonstrated that inlet valve control algorithms are practical within the steady state range of the valve, but during the non-steady state periods these algorithms do not control effectively. Basically, the valve control system will work very well if consistency can be maintained in the mixer output and it is the correction of any upstream inconsistencies which should be given priority over trying to increase the valve's control range capabilities.

If it is desirable to maintain a more uniform flow in the propellant line than can be supplied using the current inlet valve/vacuum control feed system, the replacement of the inlet valve with a positive displacement propellant pump (single screw preferred) represents a good alternative. The pump would be set-up in a similar manner to that currently proposed for the Yellow Creek booster pump: the pump would be mounted below the surge pot or as close to the surge pot as practical, the screw speed would be determined by the rate of flow through the mixer, and the pump would be run flooded. Because vacuum and gravity would no longer be the only driving forces between the mixer discharge and the Rotofeed, the Rotofeed could be installed at some distance from the mixer. This system would make overflow of the surge pot much less likely because of its robustness towards differences in propellant viscosity (e.g., the inlet valve sometimes plugs when the propellant becomes very viscous), as well as greatly increase the metering capability of the system. Although the use of a pump beneath the surge pot would not necessarily require movement of the Rotofeed into another room, space around the mixer may not be adequate for two pumps.

2.6.3 Rotofeed

The Rotofeed can process ASRM propellant quite acceptably as long as the unit is properly sealed. It is recommended that the rigorous seal installation and testing program used at the pilot plant be continued at Yellow Creek to avoid the difficulties encountered during run CMPP-020. Aside from this, the Rotofeed is a very robust piece of equipment. The following observations have been made on the steady state operation of the Rotofeed.

Rotofeed conical jacket should be [illegible] at the same temperat[illegible] the surge pot, which is maintained at [illegible] discharge temperature of the propellant. This temperature should be kept high in order to reduce the propellant's viscosity and improve deaeration efficiency. The propellant pump section of the Rotofeed should be maintained at a lower temperature. The temperature selected should be based on producing a propellant outlet temperature of between about 135 and 140 °F.

2. The Rotofeed vacuum level should be maintained as high as feasible. The designed experiment and other continuous mix runs indicate that the vacuum level becomes increasingly more important to mechanical properties as the mixer discharge temperature drops. This could be due to the increased viscosity of the propellant within the deaeration section of the Rotofeed and the decreased vapor pressure of any volatiles present. In either case, vacuum levels above 29 in of Hg are recommended.

3. The Rotofeed screw speed has not been shown to cause a significant affect on propellant properties. Therefore, the screw speed should be set based on pumping considerations. The pilot plant found that 20 % excess capacity above the flooding threshold was insufficient for maintaining uniform flow. During the extended run, a screw speed equivalent to a 50 % excess capacity was used with good results.

4. The pilot plant has found that the pressure transducer located at the entrance to the pumping section is the single most important piece of instrumentation available for controlling flow through the Rotofeed. This device will only read a positive pressure when the pumping section flights have become fully filled, an indication of flooding. If this sensor is not available, the Rotofeed power draw can also be used to indicate flooding, but power draw readings are not as clearly defined as the pressure changes.

5. The Rotofeed, being a positive displacement pump, is capable of generating very high pressures. It is essential that a pressure relief device be set up at the outlet to the Rotofeed prior to any line valves. The pilot plant uses a gas loaded piston relief valve/surge dampener; it is possible

that a va[illegible] of this concept could also reduce pressu[illegible]s. It should be added that running the pump in a flooded condition with little or no discharge will result in a substantial increase in the propellant discharge temperature. This could occur if one or more valves are closed downstream of the Rotofeed while it is running. An overpressure shut off on the Rotofeed is recommended for extreme pressure fluctuations caused by such abnormal conditions.

6. In order to seal the vacuum at start-up, the Rotofeed has both an inlet and outlet valve. The inlet valve should be opened to its cracking position (about 12 %) as soon as enough propellant is present within the surge pot to fill the inlet line to the Rotofeed. This will effectively remove the trapped air in the line without feeding any propellant into the deaerator. After cracking the valve, the valve should be quickly opened to its normal operating position (about 29 % at the pilot plant). If the level within the surge pot continues to increase, monitor the pump inlet pressure transducer and start opening the valve further. As soon as pressure is seen at the transducer, shut the valve back down to the steady state position. The latter action should be conducted rapidly because the increased valve opening is caused by the presence of viscous propellant at the valve; this viscous propellant is generally followed by thin propellant and if the valve is left in a wide open position, flooding will result. The outlet valve should remain closed until the discharge piping becomes full as indicated by an increase in pressure at the Rotofeed discharge. Since the pressure rises very rapidly at this point, the control system is used to open the valve based on a 10 psig reading at the Rotofeed discharge. In addition, the relief valve should be set at a lower than normal setting (35 psig rather than the normal 95 psig) to avoid large Rotofeed overpressures caused by slow valve reaction time.

7. At the conclusion to run CMPP-026 (inert run), a test was conducted to determine whether the Rotofeed could be cleaned by passing rice hulls through the unit. The vacuum port was removed along with the inlet and outlet piping to the Rotofeed. Rice hulls were then place in the Rotofeed through the vacuum port and the Rotofeed was turned on. It was found that virtually no rice hulls exited the Rotofeed despite Rotofeed power readings exceeding 12 kw. Upon disassembly, it was found that the conical and pump

sectio[illegible] as the last discharge flight were free [illegible]nt. However, just beyond the last discharge flight, a thick combination of rice hulls and propellant were compressed in a ring aroung the Rotofeed shaft. Rice hulls backed up in the pumping section behind this ring resulting in the scoring of the pump section wall and screw flight tips. The scoring was most evident at the pump inlet, but some scoring was noted across the entire pump section. The rice hulls cleaned well as long as they were conveyed, but the screw flights end at the pump discharge and, without the assistance of gravity or any other mechanical action, the rice hulls were incapable of producing the pumping pressure required to remove the blockage. It is not recommended that rice hulls be used for cleaning the Rotofeed at Yellow Creek.

2.7 Damage Control System

The damage control system is set up to prevent propagation of a flame front through the propellant line. It accomplishes this task by sealing off the line and ejecting propellant from the sealed off section using pressurized water. Recent tests conducted by AAD have shown that the flame front associated with ASRM propellant in Yellow Creek sized lines is relatively slow. This is an important finding in that it calls into question the very rapid initiation of the damage control system originally planned. The very fast response times do not permit much time for ensuring that the fire command is an accurate response to the situation at hand. In particular, the pilot plant has experienced numerous false thermocouple readings. Some of these false readings have occurred across groups of sensors. Without adding some time for ensuring that the thermocouple temperature is in fact valid, the possibility exists that the system will be fired accidently. Yellow Creek has taken some steps to remedy this problem including the use of "voting" procedures between three adjacent thermocouples; this may work since the thermocouples are suppose to be installed totally independent of each other. However, it is recommended that the logic required to fire this system be the subject of extensive review as the consequences of firing this system accidentally or failing to fire the system as required are very severe.

2.8 Densitometer

[illegible] pilot plant uses a Ronan densitometer. [illegible] Ronan unit contains a radioactive source and an ionization chamber for detecting the amount of gamma radiation passing through the propellant as it flows down the propellant pipe line. The amount of radiation reaching the chamber decreases as the density increases. The device has experienced significant difficulties throughout the program. Some of these difficulties were due in large part to malfunctioning boards within the meter's control box which have since been rectified. Some of these difficulties are due to calibration procedures which are difficult to perform. The latter difficulties have been mitigated to a large extent by using glycerol as a referencing standard and live, as processed propellant for the calibration point. Calibration plates can, after initial calibration, be used to obtain fairly reliable results. Unfortunately, the Ronan source's shutter compounds the difficulties involved in obtaining a proper reading. The shutter does not open to the same position on a uniform basis and this causes a change in the amount of gamma radiation available for passing through the propellant. Since the gamma radiation can either be greater or smaller for a given run, the detector can erroneously give either a high or low density reading. Fortunately, the calibration difficulties do not appear to prevent the device from detecting changes in propellant density. The unit has consistently produced density numbers with similar variability to the cured propellant density measurements made by the lab. It is believed that a device similar to that used in the pilot plant can be useful in indicating small changes in density, but probably is not suitable for estimating the actual value of that density unless the source shutter problem can be eliminated.

2.9 Propellant Pump

2.9.1 Surge Suppression

The propellant pump used at the pilot plant is a twin screw Warren brand pump. The pump is installed between the Rotofeed and the direct cast area and serves the purpose of a booster pump. Because of its position, the propellant pump is unable in and of itself to control its own inlet flow based on screw speed. If its screw speed is set at a value below what is required to transfer the in coming propellant, propellant will accumulate either by being vented out of the line or into a surge suppression system. The surge suppression system can be opened or closed. At the pilot plant, a closed

. suppression unit has been installed. .. .ce acts like an elbow under normal flow conditions, but, at the higher pressures associated with incomplete propellant transfer through the pump, a piston in the tee begins to open. If it opens far enough, propellant will be vented. As the inlet flow subsides, the piston will resume its earlier position by displacing the excess propellant back into the propellant pump. An alternate surge suppression device would be similar to the surge pot used for the Rotofeed. However, this device would require particular care to prevent the incorporation of air into the propellant since it is an open design.

The method chosen for handling these feed upsets determines, to a large extent, what type of method is most suitable for controlling the propellant pump. Using the closed surge dampener method, the best control strategy involves running the propellant pump at a speed well above its flooding point (this is the manner in which the Rotofeed is run). Since the average flow does not change, this system will generally pass whatever is transferred to it down to the cast area. Occasionally, the flow into the pump might exceed the pump's capacity resulting in back-up, but this will only occur for brief periods of time if the Rotofeed is being controlled properly. The surge dampener or closed surge suppression device is quite suitable for handling these types of upsets. If, however, an open surge suppression device is used, the pump speed will vary with time based on either level or weight. This involves an additional control loop. Failure or fluctuation within this loop could cause an overflow of propellant or the introduction of air into the propellant. In addition, the measurement of surge pot weight could fail to detect a rathole through the center of the pot, and the measurement of level could fail to detect a bridging skin of propellant located well above the actual surge pot level.

Perhaps the most important difference between the two methods is the concept of first-in-first-out. The closed surge suppression device ensures that old propellant will not buildup at the entrance to the pump, while the open surge suppression design almost ensures that old propellant will buildup at the entrance to the pump. This old propellant will cure and this could lead to a plug which defeats its ability to change levels with fluctuating flows and possibly lead to the introduction of air through or around the plug. If this plug of partially cured propellant should ever enter the pump, it would be chopped up into the propellant stream in a potentially

..zardous operation leading to the pot... ...ids or debonds within the motor to be cast.

Finally, in addition to the earlier points, the piping arrangement for the surge pot device would require a sealing system similar to that used for the Rotofeed. Such a system will lead to otherwise unnecessary valves to isolate the propellant pump and/or the surge pot.

The Warren pump was operated in runs CMPP-026 and CMPP-027 in a starved mode using the closed suppression device with good success. Occasionally, the surge dampener device was forced to move in response to changes in flow from the Rotofeed, but the system quickly restored itself as soon as the flow rate from the Rotofeed decreased. From a control point of view, this system is very simple and reliable and highly recommended for use at Yellow Creek. The open-top surge pot is not recommended for the reasons outlined above. In the event that the closed top method is used, the surge dampener should be modified to serve only the surge suppression requirement and a secondary device should be added for pressure relief purposes.

2.9.2 The Propellant Pump

The input to the pump varied with variations in flow rate through the Rotofeed inlet valve. These variations led to significant changes in the inlet pressure to the propellant pump with occasional readings exceeding 30 psig. The pump is quite capable of handling such pressures as long as the seals can maintain their integrity. If a surge pot is used, the pressure at the pump inlet will not vary to this degree, but use of the closed suppression system will result in increased seal pressures unless a sufficiently large surge chamber is used to permit level control within the dampener. In the latter case, the position of the floating piston would determine the speed of the propellant pump (e.g., if the flow rate into the pump increases, the piston rises causing an increase in pump speed). Although this system would require a periodic ejection of propellant from the surge chamber back into the propellant pump to prevent the problems pointed out above for the open surge pot design, it has the advantage of permitting reasonably good seal pressure control.

The pump has four shaft seals. The seals are difficult to install, but, once installed properly, they are capable of preventing either propellant

migration out of the pump or air mig[illegible] into the pump. Probably the worst part of the Warren design is the requirement to remove the shafts [illegible] pump. Because the pump was designed to be installed and left in [illegible] and not to be broken down repeatedly, it is anticipated that a [illegible] amount of labor will be involved in maintaining this pump. [illegible] The seals on the pilot plant propellant pump are slightly [illegible] those used on either the mixer or Rotofeed shafts in that the [illegible] are not split as they are on the other devices. In addition, [illegible] are physically very small and it has been difficult to insert these [illegible] without deforming the sealing surface. In order to improve the sealing, O-ring spacers were used between the Teflon packing and the lip seals to [illegible] added clearance and, in so doing, avoid deformation of the seal. This arrangement has provided satisfactory sealing.

Due to its clearances, the Warren pump experiences a significant amount of slip during propellant transfer which should be taken into account for the Yellow Creek system. It should be noted that under pilot plant conditions (which are different in many ways from the manufacturing plant) the outlet pressure from this pump varied significantly. If the pump is designed to maintain a steady flow using the open surge pot design, these pressure variations will cause increases and decreases in pump output for a given speed leading to some cycling of the pump controller.

The propellant pump used provided adequate transfer, but it is believed that there are substantial advantages to be gained by using a second Rotofeed instead of a twin screw pump. These advantages include fewer stocked parts for the mix facility, additional deaeration of the propellant, elimination of the difficulties involved in removing the twin screws during clean-up, reduction of inlet pressure on the rotary seals, diminished possibility of air leaks into the propellant, elimination of the ignition event risk associated with a timing gear failure or misalignment leading to flight-to-flight screw contact, and additional mixing action on the propellant.

Regardless of the pump used it should be jacketed and the temperature should be set so as to produce a propellant discharge temperature of 135 °F.

2.10 Process Control System

1. The pilot plant uses three primary metering pumps, two feeders, a propellant pump, and a variety of other variable speed drives. Serious difficulties have been encountered because of the differences between these many devices. It is recommended that uniformity in drive controls be maintained to the greatest extent possible, and the drive controls selected for use must be selected to be fully compatible with whatever overall control system will be used. On most metering pumps, the drive system can be readily selected by the purchaser. If this is not done each v[illegible] a different controller. In the area of LIW feeders, the feeder[illegible] should be forced to demonstrate the compatibility of the fee[illegible] the overall control system on site.

2. The location of the control room was no[illegible] continuous mixing over extended time periods. The control room should be accessible at all times during a run.

3. Each ingredient feeder subsystem requires precision exceeding reliable, robust analog control capability. Each feeder control system should be stand-alone with status and setpoints communicated via digital methods.

4. Each feeder subsystem should have stand alone capability for maintenance, trouble-shooting, cleaning and calibration. This should include all relevant system status, pressures, etc.. Local operator switches and lights should be at each device to handle all required subsystem operations including the ability to control start/stop and local/remote functions.

5. Panic override or emergency stop stations should be located in convenient locations near the equipment commonly operated during normal operations.

6. Alarm and status type messages need careful filtering to prevent operator sensory overload. Possibly a single message could be substituted for commonly occurring groups. Non-critical messages should be sent to a separate maintenance operator.

In addition, wh[illegible] [illegible]t plant alarm system is very useful fo[illegible] locating and correcting problems, at start-up, the system was overwhelmed by alarms due both to actual physical problems as well as to nuisance alarms. The nuisance alarms tended to mask important alarms causing items to remain uncorrected for several runs at a time. It would be wise to set alarm limits at conservative levels during the early runs to help cut down on the total amount of alarms recorded. This should improve troubleshooting during activation.

7. During pilot plant activation, each individual part and sensor needed to be accessible to the operators. With time, the various subsystems have become sufficiently robust to link together in a higher-level manner. The pilot plant, at this time, is still several runs away from a complete automatic mode of operation equivalent to a global on or off switch. This implies that operators at Yellow Creek will need to be experienced, and that operator-to-operator variations will affect run performance until this higher level of automation is achieved. Be sure that sufficient subsystem and practice run testing is planned to provide for this evolutionary process. These tests should be judged based on experience gained and level of automation advanced rather than on propellant quality or number of shut-downs. Attempting to activate the full-up system without providing time to conduct this testing will lead to schedule delays.

8. On-line analytical equipment for verification of propellant and feed stock quality is required to make real-time quality control practical. Methods of diverting non-qualified material should also be addressed.

3. ATTACHMENTS

3.1 Studies Conducted In Support of the LSPDT Development Plan

Paragraph 3.1.1 Fuel Preparation

Objective: Develop design criteria for the selection and evaluation of equipment to be used in the preparation of premix and final fuels.

Studies: Determine Physical Properties completed 8 May 1992 by R. G. Lyon.

Paragraph 3.1.2 Ingredient Metering

Objective: Develop design criteria and test and select specific equipment for the batch metering of raw materials to be used to prepare the propellant premix.

Studies: Solids Incorporation Study, TP-3002, completed 21 January 1992 by R. G. Lyon.

Liquid Conveying Study, TP-3003, completed as part of premix metering study TP-4011.

Solids Feeding Study, TP-3004, completed 30 June 1992 by R. G. Lyon.

Paragraph 3.2.2 Oxidizer Conveying Systems

Objective: Develop design criteria, evaluate candidates, and select and optimize systems which will be used to convey oxidizer.

Studies: Particle Attrition Study, TP-2001, completed 11 June 1991 by J. J. Wood.

Fluidization Characterization Study, TP-2003, completed 4 August 1992 by J. J. Wood.

Evaluation of Alternative Systems, TP-2005, completed 25 October 1992 by J. J. Wood.

Paragraph 3.2.3 Automatic Sampling Equipment

Objective: Develop sampling systems to ensure representative samples are obtained to provide reliable information for process control.

Studies: Sampler Reproducibility Study, TP-2004, completed 18 May 1992 by J. J. Wood.

Paragraph 3.2.5 Oxidizer Hopper Design

Objective: Develop and evaluate hopper design criteria to ensure uninterrupted flow of AP at the Yellow Creek production facility.

Studies: Evaluate Simulants completed 11 September 1990 by J. J. Wood.
Evaluate Alternative Flow Agents completed 18 September 1990 by J. J. Wood.
Validate Test Results completed 21 December 1990 by J. J. Wood.
Evaluate Existing Hopper Designs completed 15 August 1990 by J. J. Wood.
Select Oxidizer Flow Agent complete 31 October 1991 by J. J. Wood.
Effects of Time Consolidation and Evaluation of AP Blends completed 15 August 1990 by J. J. Wood.

Paragraph 4.1.1 Pilot Plant Subsystem Testing

Objective: Evaluate individual feed systems of the continuous mix process to obtain detailed design criteria to aid in the design, selection, characterization, and optimization of specific equipment for the Yellow Creek facility.

Studies: Oxidizer Feeder Calibration Study, TP-4002, completed 7 October 1991 by B. C. Lippsmeyer.
Oxidizer Feeder Mechanical Study, TP-4003, completed 30 September 1991 by B. C. Lippsmeyer.
Metered Oxidizer Conveying System and Optimization Study

completed 14 August 1992 by B. C. Lippsmeyer.

Premix Feeder Selection Study, TP-4011, completed 10 December 1991 by R. G. Lyon.

Premix Feeder Optimization Study, TP-4012, completed in conjunction with TP-4014.

Premix Feeder Reliability and Optimization Study, TP-4014, completed 10 February 1992 by R. G. Lyon.

Final Fuel Feeder Selection and Optimization Study, TP-4016, completed 5 March 1992 by K. T. Clemons.

Paragraph 4.1.2 Pilot Plant System Operations

Objective: Utilizing the pilot plant as a test bed, develop control and operating strategies for the safe and efficient operation of the Yellow Creek plant.

Studies: Inert Activation Run, CMPP-017, completed 12 June 1991 by J. D. Robinson.

Live Activation Run, CMPP-018, completed 8 July 1991 by J. D. Robinson.

Duel Final Fuel Run, CMPP-019, completed 1 August 1991 by J. A. Campbell.

Processibility Run, CMPP-020, completed 4 October 1991 by J. A. Campbell.

Rotofeed Test Plan, CMPP-021, completed 21 February 1992 by M. J. Mugnaini.

Rotofeed I Run, CMPP-022, completed 10 January 1992 by J. A. Campbell.

Rotofeed New Screw Test Plan, CMPP-023, completed 21 February 1992 by M. J. Mugnaini.

Rotofeed II Run, CMPP-024, completed 20 March 1992 by J. A. Campbell.

Propellant Pump Test Plan, TP-6001, completed 20 May 1992 by M. L. Wirth.

Process Response Taguchi I, CMPP-025, completed 28 July 1992 by J. A. Campbell/K. T. Clemons.

..st Area Activation Run, CMPP-026, c... 17 September by J. A. Campbell/M. L. Wirth.

Extended Run I/Confirmation, CMPP-027, completed 25 September by J. A. Campbell/M. L. Wirth.

Paragraph 5.2.2 Continuous On-Line Density Measurements

Objective: Establish reproducibility and sensitivity of alternative densitometer designs. Develop a method of quickly and reliably calibrating the production scale density measuring device.

Studies: Densitometer Study, TP-5002, completed 25 September 1992 by M. J. Mugnaini.

Eighth Annual

Continuous Mixer and Extruder Users' Group Meeting

ADDENDUM

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K-TRON SODER

October 5, 1995

Mr. David Fair, Commander
Advanced Systems Integration Division
Attn: AMSIO-IRA.W Building 172
Picatinny Arsenal, NJ 07806

Re: Eighth Annual Continuous Mixer & Users Group Meeting

Dear Dave:

It was a pleasure to see you again at the Users Group Meeting and to participate in the discussions on feeding of energetic materials. Per our conversation, I have enclosed an article on processing micropellets. This is an interesting article and I hope you find it of use in the industry. As you will see, these materials lend themselves to very accurate feeding and efficient processing within the extruder.

During the two days of meetings, there were several problems brought up concerning continuous feeding and feeders in general. During individual discussions and the panel discussions, it became evident that many of these problems are attributable to using feeders/controls that were designed and shipped in the 1980's. State of the art technology in feeders and controls is two generations ahead of equipment that is presently in place. Current equipment design incorporate features that specifically address the problems discussed during our meeting.

Unfortunately, I was uanble to compile a paper for the meeting. However I am enclosing for your review a paper entitled, "Trends in Continuous Feeders for Mixing, Compounding and Blending" that was presented by Dave Wilson, Vice President of our Training Institute. I think you will find the sections on loss-in-weight feeding and controls of particular interest and also where this technology is heading in the future.

I appreciate the opportunity to attend the Users Group Meetings and look forward to our next invitation. If you have any questions or require additional information, please do not hesitate to contact me direct.

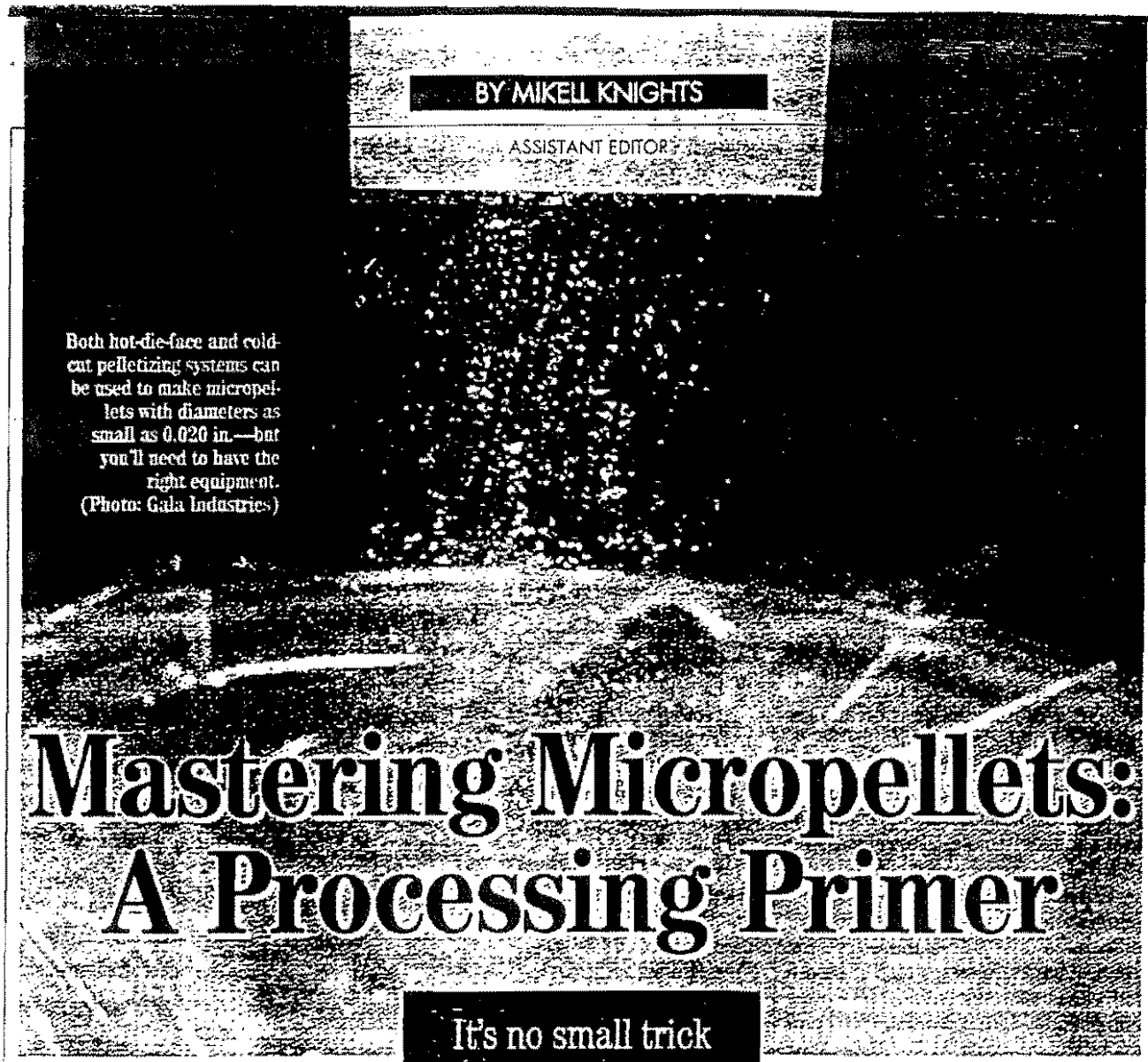
Sincerely,
K-TRON AMERICA

Bruce Lowden

Bruce Lowden
General Sales Manager

BY MIKELL KNIGHTS

ASSISTANT EDITOR



Both hot-die-face and cold-cut pelletizing systems can be used to make micropellets with diameters as small as 0.020 in.—but you'll need to have the right equipment. (Photo: Gala Industries)

Mastering Micropellets: A Processing Primer

It's no small trick to make these undersized pellets profitably. Fortunately, equipment and process know-how have evolved to meet growing demand.

You may not think of a plastic pellet as big. But the standard 1/8 x 1/8 in. pellet looks like a goliath next to the flyspecks known as micropellets.

Compounders show growing interest in making micropellets for applications from rotomolding to color and additive concentrates (see p. 44). In response, machinery suppliers have modified their pelletizer designs to produce pellets in diameters down to 0.020-0.060 in. Makers of underwater and strand pelletizing equipment say that for around $5000 a processor can retrofit an existing system to make micropellets.

Micropellet technology has been around for some 10 years, though used mainly for very specialized applications and more in Europe than domestically. Equipment suppliers say micropellets now show signs of breaking out into a larger market.

"Everyone is looking to make a pellet that is under 0.060-in. diameter," says Paul Boileau, v.p. at Rieter Corp. The smaller pellets have proportionately more surface area exposed to frictional heating in the plasticating cylinder, which reportedly leads to faster melting and more uniform mixing and melt flow. The result can be improved productivity in injection molding, extrusion, and rotomolding.

Gala Industries says micropellets constitute 75-80% of the processing tests conducted at its lab. Gala president David Bryan says his firm is developing a complete pelletizing package, including extruder (made by another firm), for micro and standard pellets. It will be introduced this fall.

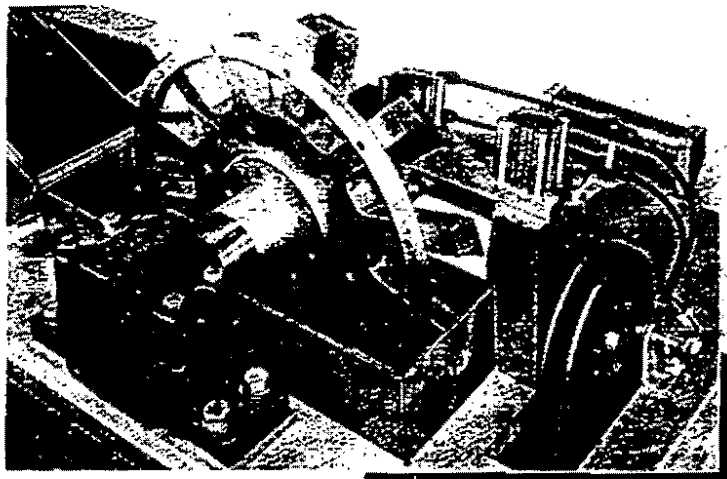
Machinery firms reporting commercial success with modified "micro" pelletizers include Gala, Rieter, Conair Jetro, Randcastle Extrusion Systems, Wayne Machine, Werner & Pfleiderer, and Black Clawson. Their equipment has been used to make micropellets of PP, PE, PS, PVC, acrylic, and PC.

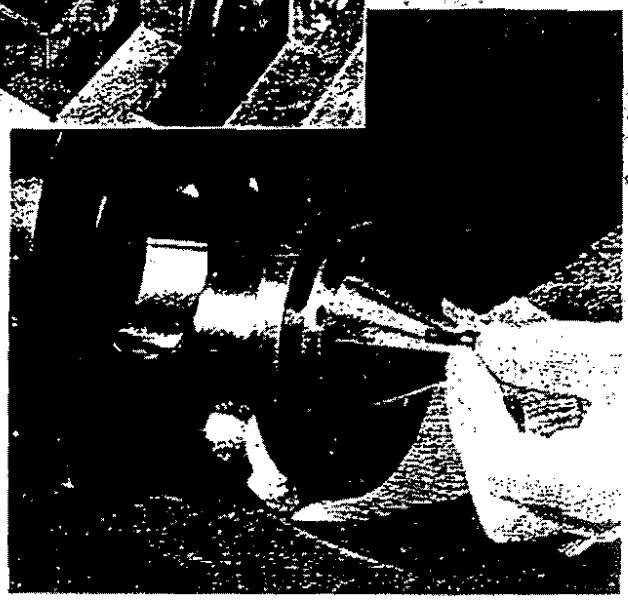
Some other suppliers, such as Beringer, are continuing R&D on micropellets, while still others—including Brimmekamp, Berstorff, Brown Plastics Engineering, American Leistritz, Reifenhauser, and Buss America—are waiting to see how the market develops.

Demand for micropelletizing equipment is coming mainly from color compounders such as Progressive Poly-

mers Inc. in Jacksonville, Texas. President Edgar Lamb says micropellet color and additive concentrates are used primarily by injection molders and extruders who want better color dispersion compared with the standard pellets, especially if they have older equipment with limited mixing capability. Like most micropellet concentrates on the market, Progressive Polymers' are highly loaded: Its 0.030-in. Color Spheres are designed for 100:1 letdown ratio and its 0.020-in. Micro Spheres are for 200:1 letdowns. The supplier charges more for the micropellets, but the customer reportedly still saves from having to use fewer pounds of material to color a part.

Micropellets benefit rotomolders by eliminating the extra cost of pulverizing standard pellets along with the sociated dust. The same is true for vinyl siding extruders, who commonly pulverize color concentrates for better compatibility with powdered PVC compounds. Concentrate maker Penn Color Inc. in Doylestown, Pa., sells 0.05-in. PVC color-concentrate micropellets for siding. In the past two years, micropellets have grown to 10% of Penn Color's sales, says plant manager Howard DeMonte.





Left: Conair Jetro's Model 2512 Fan Cutter strand pelletizer was developed specifically for cutting micropellets.

Below: Gala Industries' removable center die lets a customer switch easily between micropellet or standard pellet-making dies.

Not all materials are suitable for micropellets. The smaller die holes raise backpressure, so equipment suppliers warn that high-viscosity resins could be too hard to process. For example, some doubt that polycarbonate/ABS blends can be made into a micropellet.

PROCESS CHANGES

Micropellets can be made using strand, hot-die-face, underwater, or water-ring pelletizers. Most equipment makers say processors planning to run micropellets should be prepared to sacrifice at least 40% of their output rate due to differences in system pressure, drying, pellet handling, and pellet uniformity. In the case of color concentrates, the reduction in lb/hr may be offset by the greater coloring capacity of highly loaded pellets as compared with standard 25:1 letdowns.

Some equipment changes are necessary. The die and cutting knives have to be modified on all pelletizing systems. Other changes are specific to the type of pelletizing equipment.

IT STARTS WITH THE DIE

Micropellet die holes are smaller, thereby raising backpressure. For any type of die-face cutting, the holes must be even smaller than the pellets to accommodate die swell. For example, making a 2-mm pellet is said to require a 1-mm die hole. Strand pelletizers benefit from the opposite effect: The die hole should be slightly larger than the planned micropellet size, since some drawdown occurs during the stranding process, points out Randcastle president Keith Luker.

"Where you were typically getting 30-50 lb/hr per 0.125-in. diameter die hole, you are now down to 1-5 lb/hr with a die hole of 0.020-0.040 in. diameter," says Conair development engineer Walter Trumbull.

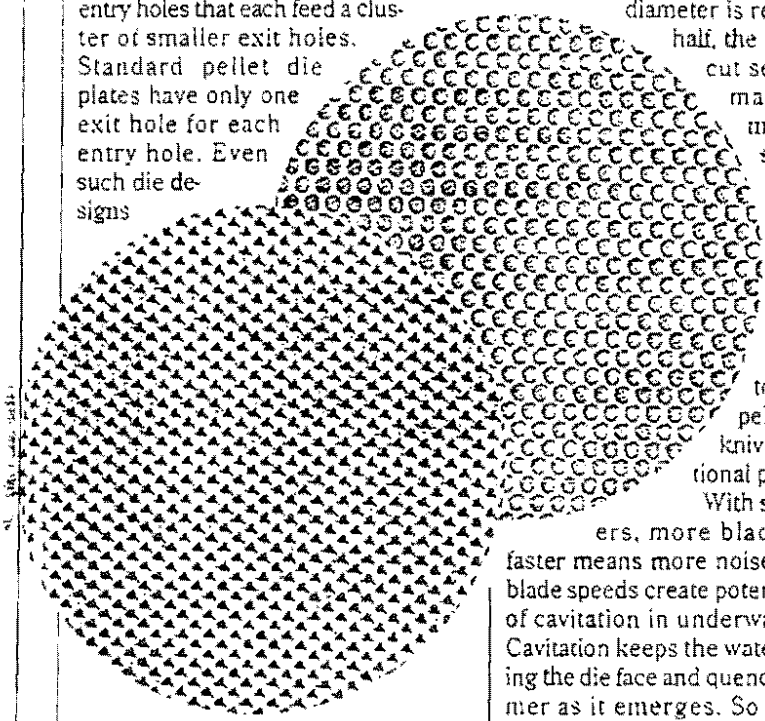
The solution is to have many more holes in the die. For example, Werner & Pfleiderer offers a hot-face micropellet die plate with 3900 holes that produces 1.3-mm pellets at about 12,000 lb/hr. Randcastle's micro strand pelletizers have screw-in die inserts so that the number of holes can be changed to balance flow and pressure requirements.

But a larger number of holes may make it harder to keep the die at the desired temperature to promote polymer flow, cautions Charles Crumb, pelletizing business manager for Black Clawson. For underwater systems running stiff-flowing materials or resins that cool quickly (like nylon), each hole needs more attention to heating so that freeze-off doesn't occur in the smaller holes. Gala recommends using hot oil or steam rather than electric die heating to provide greater temperature uniformity.

Wider spacing between die holes is thus required to accommodate more heating elements, leading to a bigger die. "When you go with micropellets the equipment gets larger," agrees Gala regional sales manager John Linken-

hoker. And with strand pelletizers, too many die holes can make strand handling more difficult downstream.

In order to minimize pressures, micropellet die designs feature larger entry holes that each feed a cluster of smaller exit holes. Standard pellet die plates have only one exit hole for each entry hole. Even such die designs cannot make pressure problems go away entirely. "In 80% of the cases, higher pressure will result [when making micropellets]," says Linkenhoker. To reduce pressure, he suggests decreasing screw speed (though that reduces output) and using a larger-mesh screen pack. However, the latter could let through more contaminants and lead to hole plugging and lower output.



Dryers will need a finer screen mesh. Gala Industries tightened the mesh of its centrifugal spin dryer to 0.016 in. (front) to handle micropellets. Screen mesh size for drying standard pellets is 0.075 in. (rear).

Conair's Trumbull suggests die lands be shortened to reduce pressure with high-viscosity materials. But lower pressure could cause greater die swell.

Joseph Cannelongo, consultant to Gala Industries, says a gear pump can help overcome pressure problems, but a pump adds more heat history, which could affect temperature-sensitive materials such as PVC.

CUT 'EM SHORT AND FAST

Equipment makers say more cutting blades and higher rotor speeds are needed to achieve abbreviated pellet lengths. Theoretically, if the hole diameter is reduced by one half, the blades have to cut seven times as many pellets to maintain the same lb/hr output. Randcastle's Luker says. His firm uses 36 knives (35 rotating and one bed knife) to make micropellets, vs. 18-20 knives for conventional pellets.

With strand pelletizers, more blades spinning faster means more noise. And higher blade speeds create potential problems of cavitation in underwater systems. Cavitation keeps the water from reaching the die face and quenching the polymer as it emerges. So hot polymer may agglomerate or the pellets may not cool uniformly. On the other hand, if the blades don't spin fast enough, polymer can stick to the blades, so output is lost or rougher cuts appear.

COOLING WITH LESS ENERGY

Water-flow rates for underwater or water-spray micropelletizing may be the same as for standard pellets, but Gala's Linkenhoker says the water temperature can be as much as 50° F higher because the smaller pellets cool faster than larger ones. Users can thereby save energy by not having to take so much heat out of the water, and freeze-off dangers are reduced.

For strand pelletizing systems, a redesign of the water trough is in order. "The water bath is significantly different [for micropellets]," says Conair's Trumbull. "It's deeper and shorter than a typical bath." Rieter's Boileau explains that because the strands are thinner, they cool faster, enabling the trough to be shorter. "If I were making a 3-mm strand of PP that would exit the bath at 80 C [176 F], it would need to be in the water for 7.5 sec. To achieve the same cooling of a strand half that diameter would take only 2.5 sec." And because there are more strands, the bath should be deeper to prevent entanglement.

Trumbull also recommends moving the bath closer to the die—as close as 1 in. For making conventional pellets, he says, the thicker strands can leave the die horizontally and then bend downward into the water. "Because the molten micropellet strands are thinner, they should go right into the bath for quenching."

Makers of strand pelletizers recommend changes to the nip rolls. Suppliers are putting motors on both rollers to control tension of the thin strands. And suppliers say the nip rolls should be smaller in diameter than for standard pellets. Smaller nip rolls allow the cutter blades to be placed closer, reducing the chance that the thinner strands would become misaligned in travel between the nip rolls and the cut.

For underwater pelletizing, the last process step—pellet drying—requires special attention. Gala developed centrifugal dryers with finer screens to hold the pellets, and the dryers themselves are wider and taller than those for conventional pellet drying. Conair has not changed the dimensions of its pellet dryer, but it has gone to a finer-mesh screen to handle the smaller micropellet sizes. □□

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Trends in Continuous Feeders for Mixing, Compounding and Blending

by

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May 17, 1995

for the

Hoechst Celanese Worldwide Technical Conference

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Continuous Feeding Equipment

Overview

Introduction

This paper deals with a brief review of feeding and the strategies used to attain precision in material delivery. I will discuss volumetric feeders, gravimetric feeders, study their operation, review control strategies, examine communication concepts and look at what is new in feeding. And after all of that, I will try to predict the future.

In this chapter

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Symbols and variables

Variable	Description	Units
a	Cross sectional area of material pile on belt, vibratory tray or disk feeder	dM^2
c	length of groove on disk feeder	dM/rev
d	Vibratory tray displacement	dM
Ω	Vibratory tray cycle rate	Hz
ß	Screw fill or rotary valve pocket fill factor. This is the design value	L/rev or dM^3/rev
μ	Intermeshed screw volume reduction factor	Decimal value
MF	Mass flow rate of bulk solid or liquid	Kg/minute
f	Fill factor for selected feeder types	%
n	Number of rotary valve rotor pockets or number of screws in a multi-screw feeder	Integer
r	Screw, disk or rotary valve RPM	Rev/minute
T	Time of sample in loss-in-weight feeders	Seconds
v	Belt or material velocity	Meters/minute
W	Weight in loss-in-weight feeder hopper	Kg
∂	Product density. The weight per unit volume of a bulk solid.	Kg/dM^3 or Kg/liter
Δ	Blade angle in a Hogan feeder	Degrees
k	Hogan feeder conversion factor	dM/(deg*min)
e	Volumetric efficiency of feeder	Dimensionless
q	The volume per pocket or cavity in a rotary valve or holed disk feeder	L or dM^3
ε	Error signal as measured between the process variable and the setpoint.	Units of measure
Σ	Comparison or subtraction	Results are units of measure
Angle of Repose	This is the angle from the horizontal that a material pile will make due to particle friction.	Degrees

Continued on next page

Symbols and variables, con't

Variable	Description	Units
Belt Loading	Belt loading is the weight of material on a weigh belt in the terms of weigh per unit length such as kg/meter.	Kg/Meter or Lb /Ft.
Bulk Density	The weight per unit volume of a bulk solid.	Kg/dM^3 or Lb/Ft^3
Drive Command	This is the output from the K-Tron controller.	0-100% - a frequency value of 0-10kHz
Refill Minimum	The weight point at which a refill is started.	Weight Units
Refill Maximum	The weight point at which a refill is terminated.	Weight Units

Continued on next page

Definitions

Item	Description
A/D Conversion	The process of electronically converting an analog signal to a digital one that can be used directly by a computer
ASCII	American Standard Code for Information Interchange
Asynchronous data transmission	Data that may change its state at any time and is not normally tied to a clock. A synchronizing element is required to align receiver and transmitter so that data is accurately received.
Baseband network	Only one signal is on the network at one time and all others are time spaced on the bus.
Batch feed systems	These systems deliver a specified amount of product to the process. e.g. 24.66 kg of sugar
Baud Rate	Is often used incorrectly and the common usage means bits/sec of transmission data rate. It really means modulation rate of the communication device.
Bridge	A device that connects two different networks of the same type. It contains physical connections and signaling.
Broadband network	Uses frequency division multiplexing or frequency spacing to keep channels apart. e.g. CATV.
Carrier band network	A single carrier on a single channel. Modulation of the signal above DC still requires time spacing.
CCITT	The International Telegraph and Telephone Consulting Committee, a standards group.

Continued on next page

Definitions, con't

Item	Description
Closed loop control	Control where appropriate feedback is used by the controller to render the process variable equal to setpoint.
Continuous feed systems	These systems deliver a specified rate of product flow to the process. e.g. 12.67 kg/minute of flour
DDC	Direct Digital Control where a control system was executed by a single computer connected to all sensors and final control devices.
DCS	Distributed Control Systems. These are computer -based systems that control multiple processes or plant wide processes. They operate over local area networks with connected processors located near the point of need.
DeviceNet™	A communication standard for field devices, simpler than Fieldbus, using Controller Area Network-CAN- technology. Sponsored by Allen Bradley.
EBCDIC	A code from IBM to define a character set from digital transitions.
EIA	Electronics Industries Association, Wash., DC.
EMI	Electro-magnetic interference
Ethernet™	Essentially the broadband communication model developed by Xerox- PARC that became the basis for IEEE 802.3 CSMA/CD LANs. (Carrier Sense, Multiple Access, with Collision Detection.
Feeder	A generic term used to describe a machine that meters bulk solids materials into a process in some sort of controlled manner.
FieldBus Foundation	A joining of ISP and WorldFIP to produce one common fieldbus standard.

Continued on next page

Definitions, con't

Item	Description
Field Bus SP-50	Communication protocols from ISA, the Instrument Society of America in Research Triangle Park, NC and IEC, the International Electro-technical Commission.
Final control element	These are the devices that define what the output flow really is. Pumps, control valves, etc. are final control elements.
Full duplex data transmission	A complex scheme to permit simultaneous data transmissions between peer devices. A system such as this use multi-tasking and interrupts to manage data flow. Data is essentially moving back and forth between devices on the same wire.
Fuzzy logic	A logic set that uses not only true/false conditions but other conditions that lead to "shades of gray" control
Gateway	Connects proprietary networks to an open network. It is a data translator, converter and signal modifier all in one.
Gravimetric or gravimetric feeder	The use of weight measurement in the operation of a belt feeder. Think of it as automatic control of a feeder process
Half duplex data transmission	A simple scheme to permit multiple devices to communicate over a one or two wire system. Generally designed for one master and one or more slave devices.
Heuristics	The use of learning to determine future control or knowledge based control. One example is control sets developed from a rules base.
IEC	International Electrotechnical Commission in Geneva, Switzerland.
IEEE	Institute for Electrical and Electronics Engineers

Continued on next page

Definitions, con't

Item	Description
Interchangeability	Similar devices from different vendors can easily be exchanged, one for the other.
Interoperability	Dissimilar devices that conform to a common specification and can function together.
ISO	International Standards Organization
ISP	Field bus that is a result of Profibus™, a product of Siemens.
Kalman Filter	A type of statistical filter for estimating the value of a process input.
Loss-in-weight feeder control systems	Loss-in-Weight Feeder - Gravimetric- A type of gravimetric feeder that uses a feeder and supply vessel, in which material is stored, mounted to a weight sensor. The withdrawal rate is measured, computed as massflow and controlled by the feeder control system and the final control element.
MAP/TOPS	G.M. and Boeing Communication protocols
Massflow	This is the computed value of flow in the process in the units of weight per time interval.
Open loop control	Control where no pertinent feedback signal is used.
OSI	Open Standards Interconnection data communications model
PI Control	Automatic control that uses proportional and integral action to stabilize and control the process.
PID	Proportional, Integral and Differential Control algorithms.
PLC	Programmable logic controller that is used for industrial control.

Continued on next page

Definitions, con't

Item	Description
Process variable	The measured variable from the process that describes the process condition.
Refill	The process of filling the LWF bin while the process is running
Router	Like a bridge but connects networks of differing types with error correction, signal conversion and data packet conversion.
RTD	Resistance temperature detectors.
Setpoint	The target value for the process.
Stochastic control	The use of statistical measures in process control where probabilistic laws are applied. Stochastic or random processes are described as a time function.
Supervisory Control System	Normally a computerized system that interfaces to many local control loops in a plant such that a single point of integrated interaction is possible.
TCP/IP	Transmission Control Protocol/Internet Protocol is used in UNIX systems that describe the Internet.
Volumetric or volumetric feeder	Manual control of the feeder process. The output of the feeder is fixed. Or a feeder that controls flow by controlling material velocity, not taking into consideration material bulk density.
Weigh belt feeder	A conveyor type feeder where the belt velocity is controlled to deliver a precise rate of bulk solids to the process at a specified setpoint.
WorldFIP	Initiated in France, a consortium of DCS providers and others joined to produce a fieldbus standard.

Why Have Feeders?

Introduction

This section will look at why feeders are required and some of the attributes that are necessary when using them for compounding applications.

Purpose of feeders

The true function of a feeder in a continuous process is to closely and accurately control the flow of bulk solid such that the product produced by the process meets quality standards with no waste due to improper performance. To achieve the desired level of performance, the selection of feeding device, the installation and operation together determine the success of the feeding process. You know that demands on the process to produce a higher quality product, one that is more uniform with no waste becomes more important each day. The proper selection of the feeder, the quality of feeder installation and the feeder operating environment are critical to meeting that demand.

Attributes

When supplying feeding equipment to a processor, there needs to be a common language between the vender and the user. A specified and recognized set of numbers is likely one way to improve the communication process. The numbers that describe feeder attributes might include the following:

Accuracy, which can be considered to be made up of three components:

- Stability or how often do I need to re-calibrate the feeder
- Linearity - How close to setpoint does the massflow come as the operator changes the setpoint value over a wide range.
- Repeatability- at a fixed setpoint, how uniform are any group of samples. These samples are taken from the flow stream.

Turndown or the range of setpoint change that can be accomplished is another measure of feeder performance.

Reliability is an issue that is not often discussed but can be measured in terms of MTBF (mean time before failure) or in % up-time. Robustness and suitability for use are also issues.

Each of these attributes determine how well a feeding system will work in your process. Can you think of other requirements that might affect how a feeder might perform in your process?

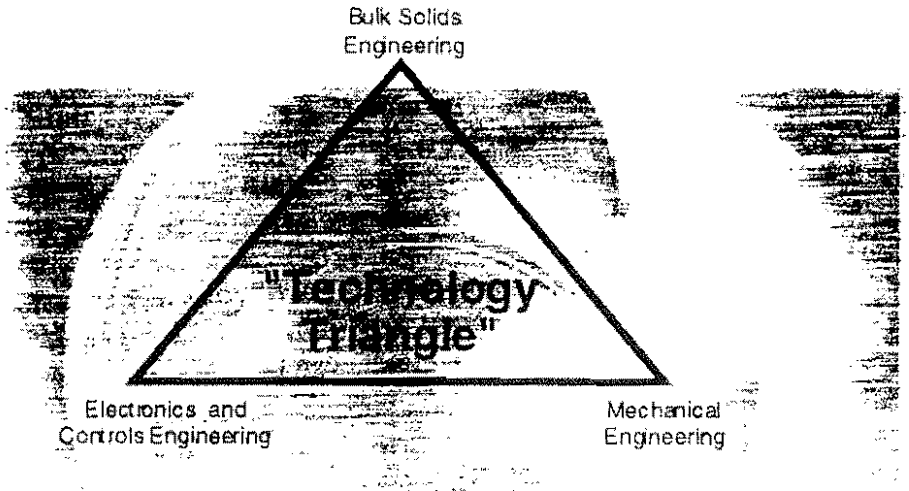
The Basics

Introduction

This section presents some basic concepts of volumetric and gravimetric feeders and introduces the idea of the Technology Triangle for Feeding.

Technology Triangle

We need to observe the ideas presented in the concept of the Feeding Technology Triangle to design and build a solidly functioning feeder . It is shown here.



The linkages on this graphic are important if we wish to build a accurate and dependable gravimetric feeder.

Since bulk solids engineering tends to be looked upon as an art by those not skilled in the field and since feeder selection has to be made based upon how well that device can meter the bulk solid in question, we need to focus on this topic first. You must understand the impact of how a particular bulk solid may affect feeder performance.
For example, if the material does not flow out of the bin above the feeder, the feeder below will not serve its purpose. In a weigh belt feeder, if bin flow above is erratic, feeder performance may be degraded. In the case of a loss-in-weight feeder, if the refill bin is of the wrong design, failure of the refill system to quickly refill the feeder hopper may result in a no flow condition to the process. The mechanical design of the feeder and supporting bins and hoppers must be of prime concern. Clearly, for volumetric or gravimetric feeder applications, knowing the flow properties of the bulk solid is critical in feeder selection and to the ultimate success of the feeder installation.

Continued on next page

Technology triangle, con't

The electronics and controls engineering portion is where many engineers focus their time since many gravimetric feeders require sophisticated controls and may be linked into process computers for supervision. Software design is now where significant engineering time is spent as designers continue to optimise equipment performance by the implementation of improved algorithms and interfaces.

The mechanical engineering aspects of feeder design include the gear boxes, metering devices and in the case of gravimetric feeders, the weighing system. The m[illegible]andle the bulk solid reliably and predictably [illegible] also plays a key role. In industrial weighing syst[illegible] must be available to the designer if a high perfor[illegible]der is required.

Finally, I suggest that th[illegible]r installation can affect feeder performance. An [illegible]nimal vibration signatures and other disturbance eff[illegible]all accuracy of flowrate.

Volumetric Feeders

Introduction

This section will focus on the various types of volumetric feeders used in the marketplace today.

Metering device-the feeder

Choices abound for metering devices or volumetric feeders. Successful ones share certain attributes. They are predictable in their flow output. They are reasonably linear in output and their transfer function is stable and definable. For a fixed input value, they provide minimal fluctuations in flow.

Feeder or metering device selection is the first avenue to explore. Choosing the right volumetric feeder is just as important as incorporating the right bin design with the feeder. This decision will depend on the desired throughput, and on whether the material can withstand being pushed out, being held back as in the case of flooding or whether it must be coaxed out more gently. There are several mechanisms available to discharge materials from the feeder to the downstream operation, these include: single-screw feeders, rotary feeders, belt feeders, vibratory feeders, disk or table feeders and vane or slat feeders. Selection of the appropriate volumetric feeder is important whether you will use it only as a volumetric feeder or add controls and a weighing system to make it into a gravimetric feeder.

Several factors are to be considered when selecting a metering device.

- √ Kind and character of material to be fed; its flow properties
- √ Density of material to be conveyed.
- √ Maximum flow rate.
- √ Minimum flow rate.
- √ Particle size and question of friability.
- √ Overall feeder length.
- √ Hopper opening dimensions.
- √ Environment and use

Think of these criteria as we investigate together, various types of volumetric metering devices.

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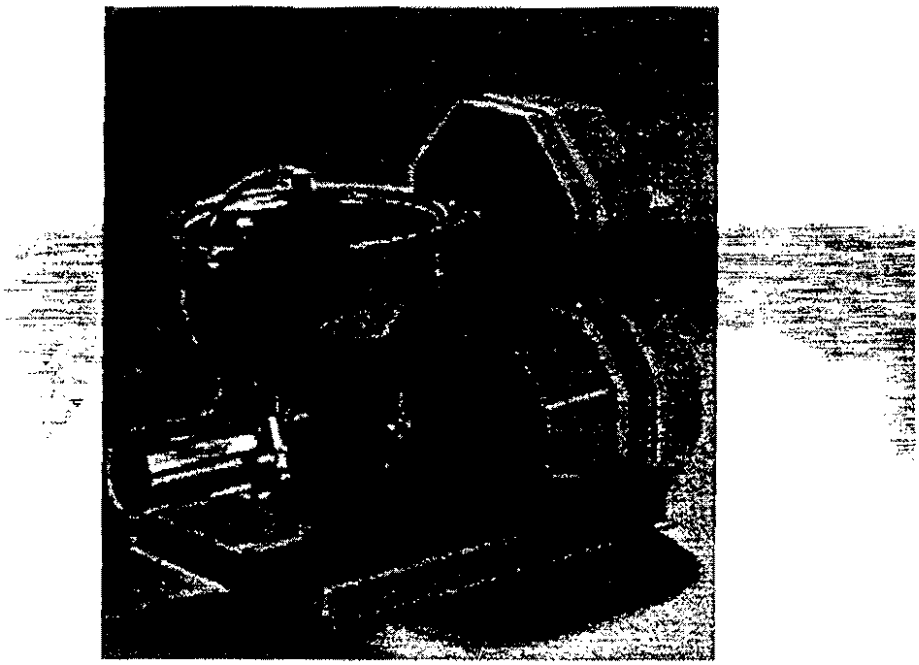
Single screw feeders

Single-screw feeders are the devices most commonly used to move powders and pellets in compounding applications. Here is an example.



Single-screw feeders are available with a volumetric capacity ranging from 0.1-56,000 dM^3/hr . They are available in several configurations, and the basic theme is carried through all versions: The volumetric flow rate is controlled as a function of the speed of a motorized, horizontal screw. Propelled by the force of its own weight, or with agitation, bulk material in the feed hopper is thrust into the flights of the screw. It is pushed by the screws through a restrictive tube, into downstream equipment. The formula that defines flow rate is:

$$MF(Kg/min) = ß*r*\partial*e$$

The value of "r" is controlled by some type of motor control system.

Continued on next page

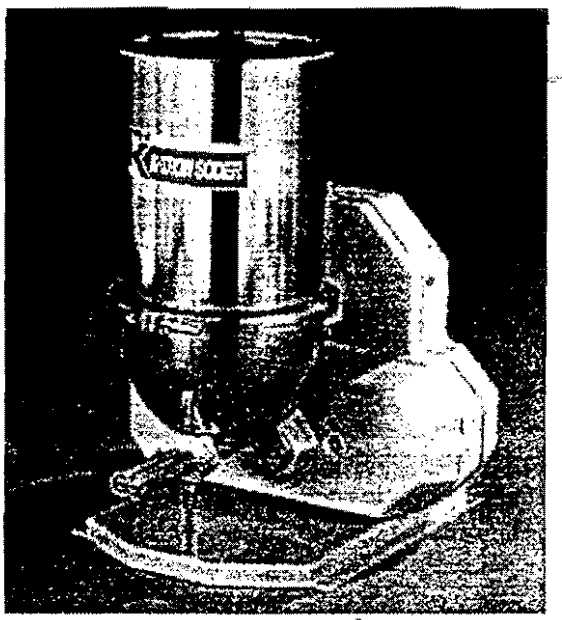
Single screw feeders, con't

Some screw feeders use a constant-pitch screw while others use a variable-pitch screw. The variable-pitch screws require less horsepower to draw material out of the overlying hopper load, and they promote uniform flow from the feed hopper, although this factor may not be so critical on smaller screw type feeders.

Single-screw feeders are relatively inexpensive, and usually require only simple maintenance. They are versatile enough to handle free-flowing powders, and granular, pelletized or flaked products, such as plastic pellets, polyvinyl chloride resins and regrind.

Twin screw feeders

The twin-screw feeder is very similar to the single-screw feeder.



The difference is one motor drives two intermeshed or non-intermeshed screws. Most designs are co-rotating- that is the discharge screws rotate in the same direction.

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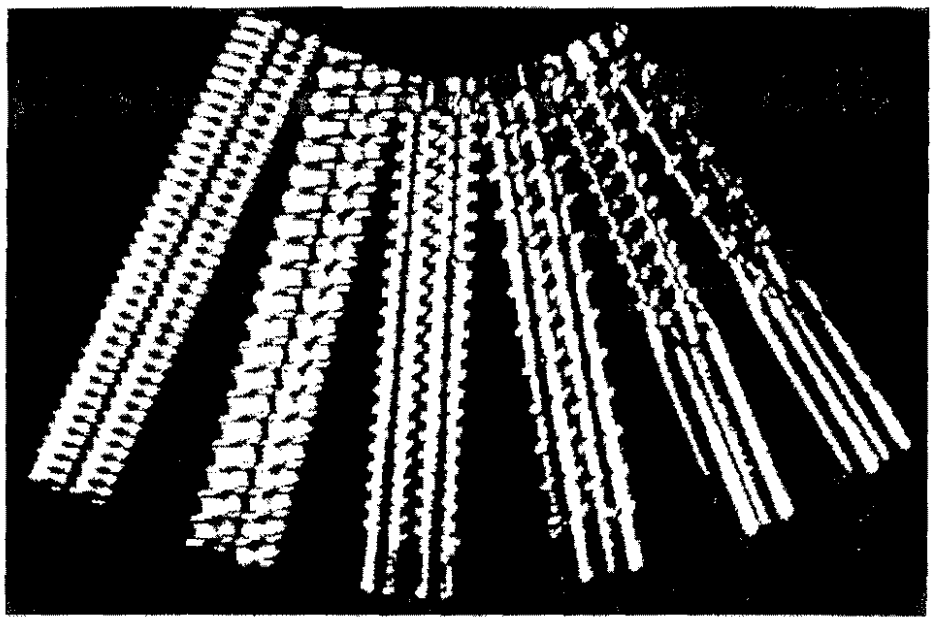
Twin screw feeder, con't

Here is a photo of typical feed screws used in a twin screw feeder.



Throughput capacity ranges from 0.2-39,200 dM^3/hr . The formula that describes the output is:

$$MF(Kg/Min) = ß*r*\partial*n*e$$

In small twin-screw feeders the close fit between intermeshed screws helps to keep floodable materials from uncontrolled discharge. Intermeshed twin screws are also adept at moving sticky materials, since the screws are self wiping. This attribute, however, may cause problems when feeding pellets, which may jam or become crushed between the two screws. If the feed screws are intermeshed, the flow formula becomes:

$$MF(Kg/Min) = ß*r*\partial*n*(1-\mu)*e$$

Twin-screw feeders are recommended for hard to handle products, such as carbon black, iron oxide, diatomaceous earth, titanium dioxide and other additives. Twin-screw feeders also offer a smoother, more-consistent flow than do their single-screw counterparts.

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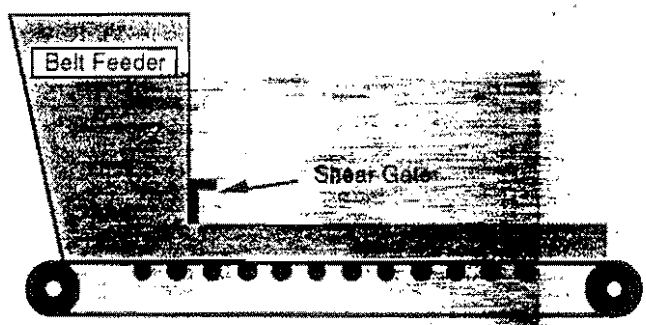
Belt feeders

Belt feeders are versatile. They are available as a volumetric metering device, or as a weigh-belt feeder in a gravimetric configuration. Through an inlet gate on the feeder itself, material is sheared from a storage hopper above and delivered to a conveyor belt. In its volumetric configuration (as a regular belt feeder), this gate discharges an adjustable profile of material to the belt.



Their low cost, simply understood maintenance, and particular adeptness for applications with high flow rates make them desirable in many industries. Such feeders are often used to extract high volumes of fragile material, granules, ores and powders, from bins and silos. Imagine feeding corn flakes in a screw feeder. Their volumetric capacity ranges from 28 - 5.6 x 10^5 dM^3/hr. Belt width can range from 150-1800 mm.. The length of the unit can run from 1 to 10 meters. Capacity of the belt feeder is determined by the belt speed and by the profile of material discharged to the belt as in the following formula.

MF(Kg/Min) = 10*v*a*∂ (assuming the measure for 'v' normally measured from the velocity of the belt equals the velocity of material on the belt)

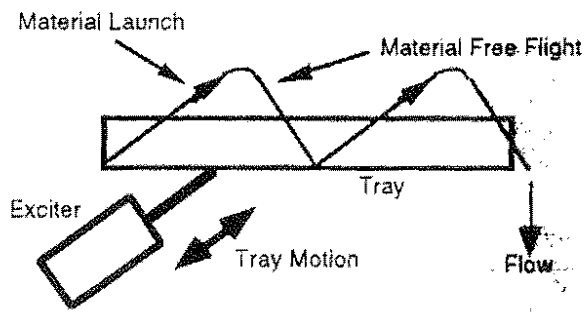
Belt speeds range from 0.3-75 m/min., with 20 m/min. considered an upper limit for smaller feeders. Higher belt speeds result in excessive belt and equipment wear, increased horsepower requirements, and cause high levels of dust if a fine product is being conveyed. Material velocity and belt velocity may not agree at high belt velocities, and since belt speed is what is measured, flow errors can result.

Continued on next page

Vibratory feeders

Vibratory feeders are used to move materials that could damage, or be damaged by screw or belt feeders. Materials such as abrasive or friable solids are held in a pan or tray in order to carry them toward the discharge point. As the pan vibrates, cyclically at an angle to horizontal, the particles hop down the tray toward the discharge outlet.

Electromagnetic energy or motors that use counterweights are common vibration sources used to set the tray in motion. Tray displacement typically ranges from 0.80 to greater than 3 mm. We see an exaggerated picture below of how material moves.



Factors for determining flow rate from a vibratory feeder include tray frequency and displacement, material flow characteristics and to a limited extent, head pressure of material on the tray. The capacity range on these feeders is from 14-1.12x10^6 dM^3/hr. Vibratory feeders use an unobstructed feed tray and are therefore useful in situations calling for frequent cleaning. But for them to convey, trays must be dry to permit controlled flow. The flow formula is:

$$MF(Kg/Min) \approx 60*d*\Omega*\partial*a*e$$

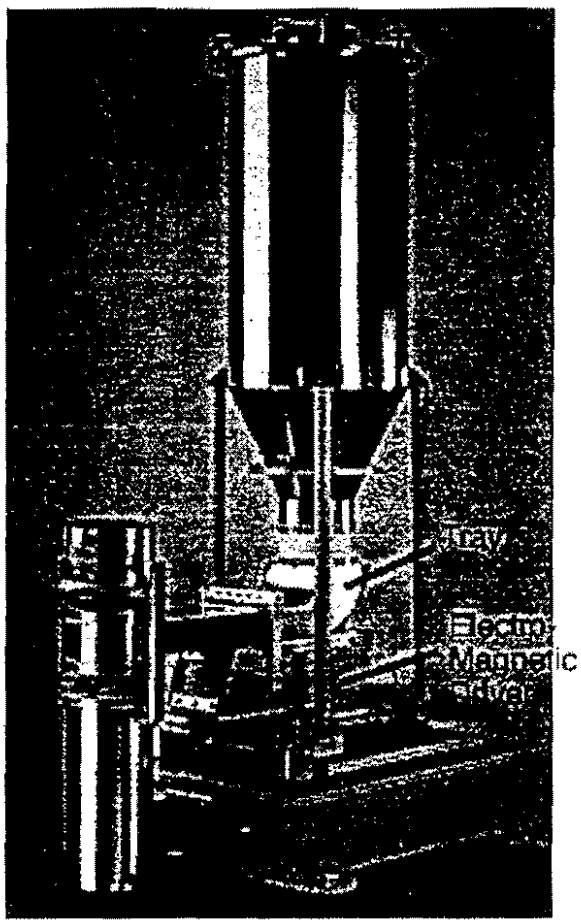
Vibratory feeders are limited in their ability to be entirely accurate in setting the rate of discharge with conventional controls, and the rate of discharge tends to vary in a set range. This non-linearity is particularly problematic during volumetric discharge, therefore frequent calibration will be required to gain the most accurate feed rates.

Continued on next page

Vibratory feeders, con't

By comparison, a well designed volumetric screw feeder has very linear turndown, making it reliable over a large range of feed rates. If used gravimetrically, vibratory feeders are more reliable, since the sophisticated control system re-calibrates the system automatically.

Here is a photo of a vibratory feeder mounted on a scale to produce a loss-in-weight feeder. You can see the tray mounted to the electro-magnet structure.



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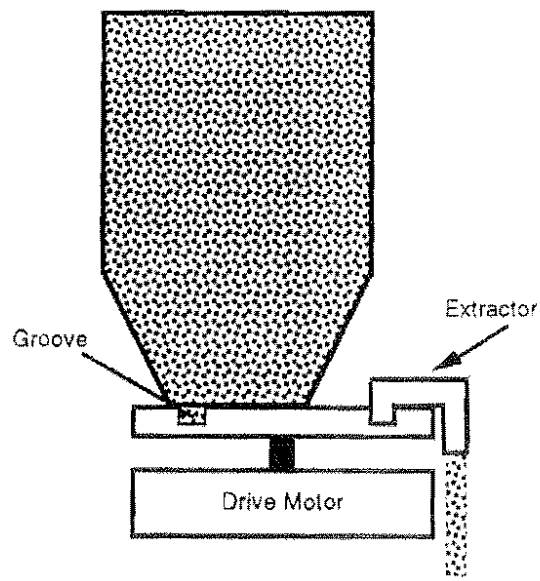
Disk feeders

Disk or table feeders have a rotating table or disk mounted off-center and sealed against the bottom of the feed hopper. As the motorized table turns, a groove in it fills with material sheared from the hopper above. Once the groove moves out from under the hopper, it is emptied by the extractor.



Flow rates are determined by material density, speed of the disk and geometry of the groove. The disk feeder, reserved for small flows of powders, has a capacity range of 0.012 -35 dM^3/hr. Disk feeders work well with materials that are highly cohesive or have very high shear. Its flow formula is similar to others already described.

$$MF = a*r*\partial*c*f$$

Continued on next page

Disk feeders, con't

A deviation of this concept uses holes in the disk rather than a groove to hold the product. Only one hole at a time deposits material to the feeder outlet as the holed disk rotates. The flow equation is

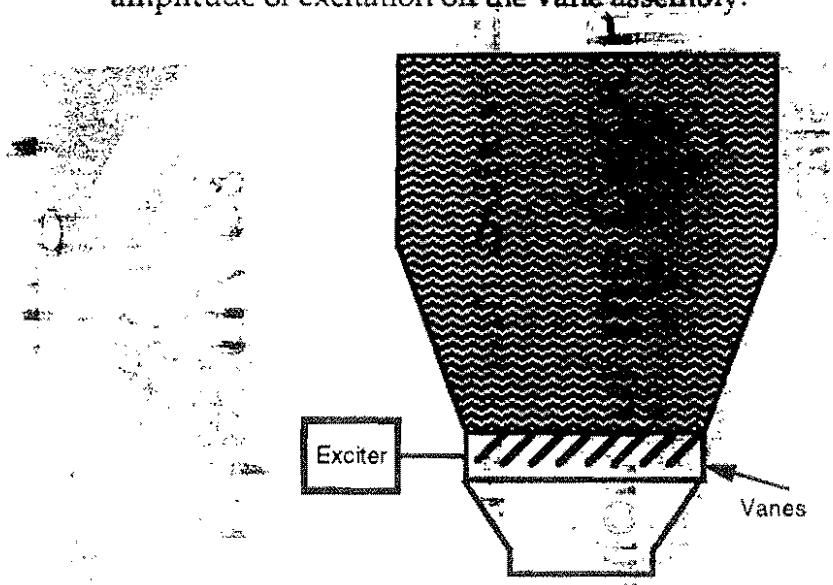
$$MF = r^*\partial^{**}f^*n^*q^*$$

A picture of the internal disk arrangement is shown below. Holes could be used in place of the edge placed cavities.

Continued on next page

Vane/slat feeders

The vane or slat feeder discharges material via its multiple vanes, which look like a venetian blind mounted horizontally at the discharge outlet. When the slats are not in motion, the material in the bin bridges over the slats. When the slats are vibrated laterally, the bridge is broken and material flows. Some designs allow the slats to be closed all the way, to prevent any flooding of fine materials. One design moves the angle of the slats to control flow. Another fixes the slat angle and controls the amplitude of excitation on the vane assembly.



The capacity ranges from 0.16 - 6.6×10^5 dM^3/hr . Mounted directly under a bin, this feeder works well with stringy materials, and with materials whose cohesive strength is sufficient to prevent flooding when the slats are open. Excitation can be by an electromagnetic drive or eccentric counter-weighted motors. For the feeder style that uses blade angles to control flow, the approximate formula for flow is:

$$MF = k^*a^*\partial^*\Delta$$

Continuous Gravimetric Feeders

Introduction

In this section, I will discuss both types of gravimetric feeders and examine their role in the continuous compounding process.

Gravimetric feeders, an intro

Most gravimetric feeders use electronic systems, generally more sophisticated than volumetric feeders use, to control the feeding process. Weigh cells of some type are included in the control scheme to reach some conclusion about the bulk density effects of the material being fed on the flow rate. However, the choice of volumetric feeder used in metering and controlling the flow rate is critical to the quality of a gravimetric feeding system.

There are two main types of gravimetric feeders used in compounding today. The first type is the gravimetric weigh belt feeder and the second is the loss-in-weight feeder.

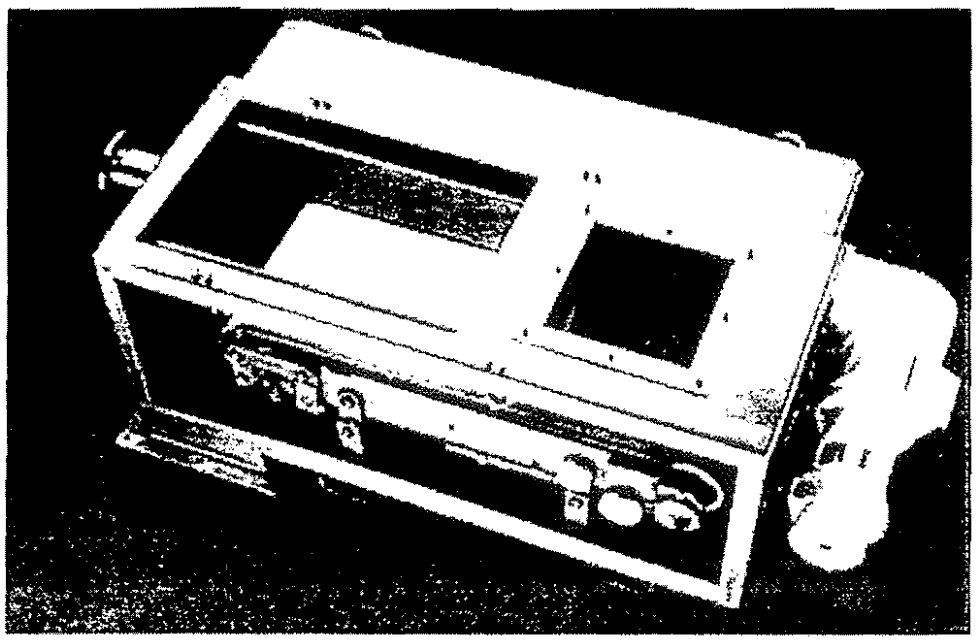
Gravimetric Weigh Belt Feeders

Introduction

This section discusses the role of the weigh belt feeder in compounding.

Function of the gravimetric weigh belt feeder

The gravimetric weigh belt feeder-WBF- is a simple device that moves product using a belt conveyor, under which, is located a weighing system . The weighing system measures the weight of bulk material per length of belt travel, converting the weight measurement into a value called belt loading. The units of belt loading are typically in lb/ft or kg/meter.



There are modifications on this theme, but let's use this case as our example. What element controls the flow? Of course it is belt speed as measured in ft/min or meters/min velocity. But what is really needed is material velocity. Is the material velocity really known? Let's see what happens when the control system deals with these values. Here are a few definitions.

BL = belt loading, (kg/m)
BS = belt velocity and hopefully, material velocity, (m/min)

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Function of the gravimetric weigh belt feeder, con't

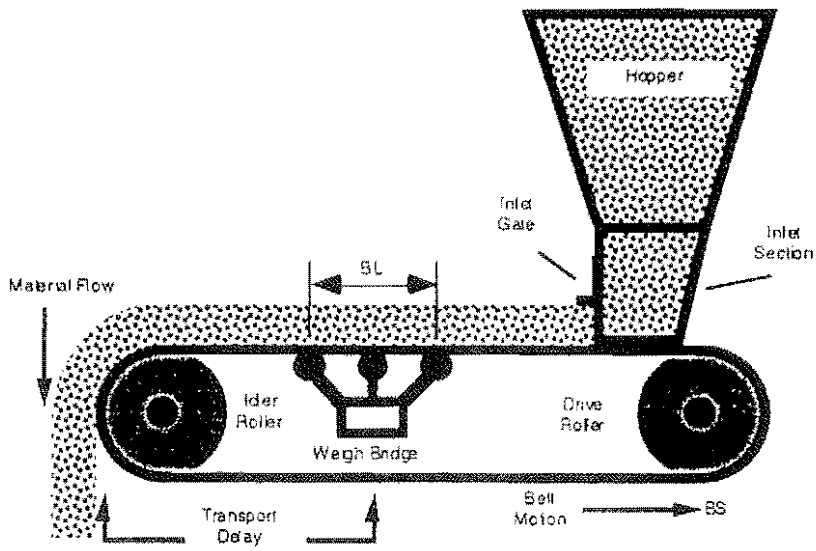
$BL_{kg/M}$ = (Bulk $Density_{kg/M^3}$)*(Cross-sectional area of $material_{M^2}$)

Mass flow$(MF)_{kg/min}$ = Belt Loading(BL) x Material Velocity(BS)

$MF_{kg/min} = BL_{kg/M} * BS_{M/min}$

To control rate at a fixed setpoint and since MF = SP, then

Belt Speed = Setpoint/Belt loading. The motor velocity is controlled.



Early feeder designs held the belt speed fixed using AC motors to drive the belt and adjusted belt loading. A servo gate adjustment which regulated the pile height on the belt or a pre-feeder which did the same thing was used. When the setpoint was reduced, so was the gate height. Now, most vendors fix the inlet section to achieve uniform product flow onto the weigh belt and vary the belt speed with a variable speed motor drive to meet the desired flow rate.

Continued on next page

Belt feeder benefits

Weigh belt feeders are an inexpensive solution when feedrates of 250 kg/hr or more are required and the material is free flowing. These feeders have low headroom requirements, low power consumption, and are compact when the flow rates become high. I also find that people use weigh belt feeders because their operation is easy to understand and troubleshooting is generally straightforward. Additionally, the weigh belt feeder can be used as a meter or flow indicator when run a constant velocity.

Belt feeder compromises

The use of belt feeders have some limitations because of the measurements used in the calculation of massflow. Both the speed of the material and the weigh per foot of material on the weigh belt are described by other measurements. The equation that correctly defines massflow is:

$MF = V_m * A_m * \partial$ where

∂ = bulk density, V_m = material velocity and A_m = material cross section

Neither of the measures that we say earlier are V_m and A_m.

This situation results in the use of inferential measurements to compute the massflow value. The feeder weighs the amount of material on the belt, through the belt, and then converts the measurement magically by a factor of weight span length to obtain the belt loading value. Since you cannot easily measure material velocity, designers measure belt speed by various methods and various transducers and hope that the material is moving at the same speed as the belt. Calibration generally must be done by catch samples to insure accurate performance. These feeders also require periodic cleaning and maintenance. However, in spite of the problems associated with the material measurements, weigh belt feeders are practical for selected applications in compounding.

Belt feeder applications

Current applications for weigh belt feeders include rate control of pelletized materials in compounding. Feeding plastic resin or pellets that have few fines and at rates well above 250 kg/hr is a common application of these devices. The feeding of some types of stranded materials is also possible.

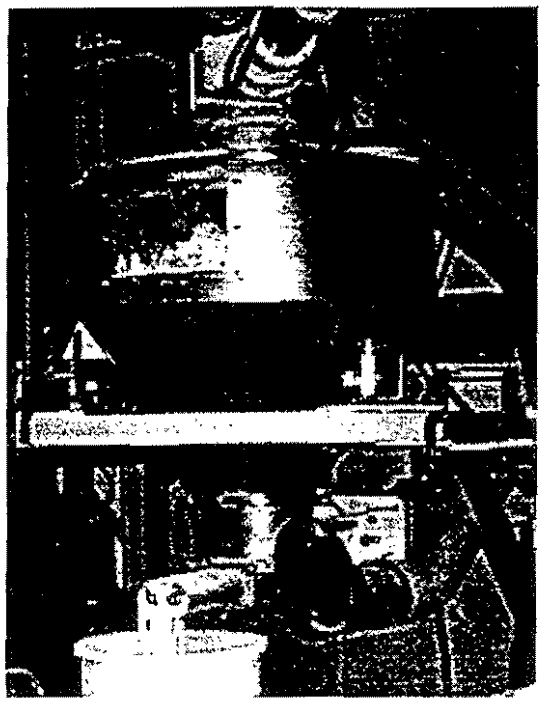
Gravimetric Loss-in-Weight Feeders

Introduction

This section discusses the role of loss-in-weight feeders in compounding operations.

Function of the gravimetric loss-in-weight feeder

The loss-in-weight feeder - LWF- weighs the contents of the feeder, mounted feed hopper and material in the hopper. Here I show an example of a loss-in-weight feeder operating in a lab.



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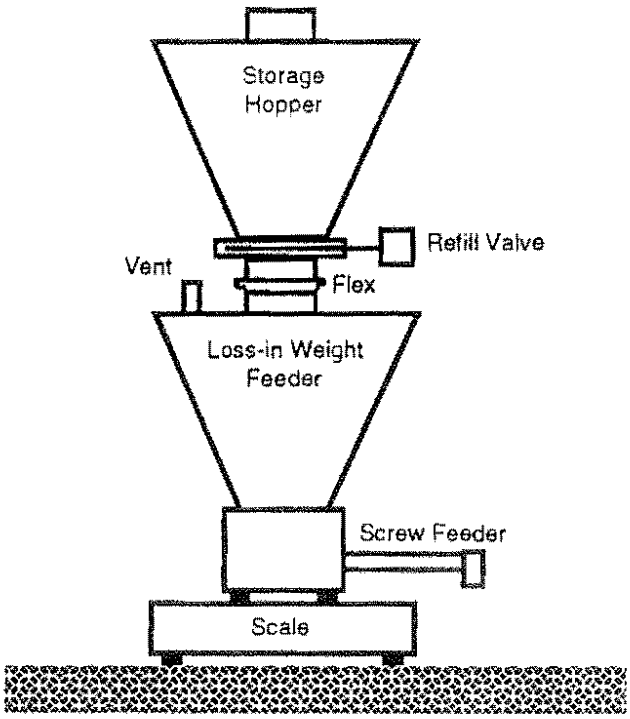
Block diagram of a typical loss-in-weight feeder

The following sketch shows the key components of a typical loss-in-weight feeder.



What is being weighed in this example? What happens to the scale readings as material is withdrawn from the feeder?

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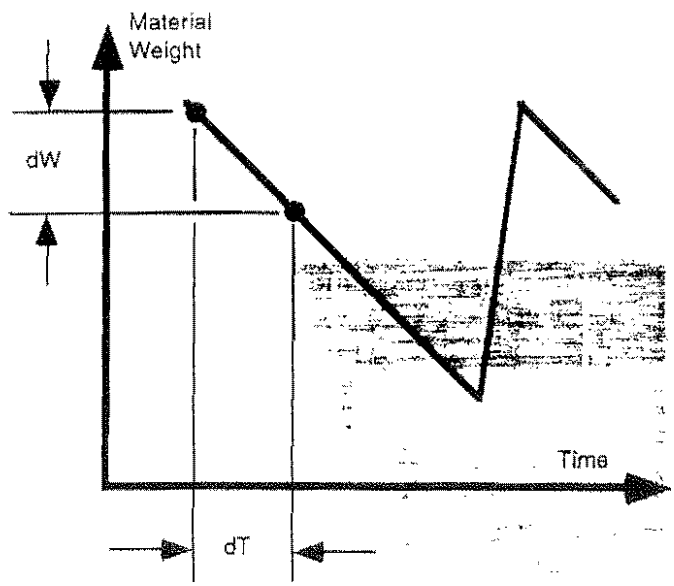
Function of the gravimetric loss-in-weight feeder, con't

As the feeder discharges material, weight decreases in the feed hopper. The upslope portion of the graph defines the refill period.



The value of [Δ weight/Δ time or dw/dt] is computed as mass flow. Once the controller has calculated the mass flow value in this way, the massflow is compared to the required setpoint. The resulting error, if any, is manipulated to control the feeder discharge device so that setpoint is achieved. Unlike the weigh belt feeder system, one of the great benefits of the loss-in-weight feeder is that it directly uses the measurements it makes of the process for control. What are the process measurements in loss-in-weight control? Weight and time are the needed measures.

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To calculate massflow of a loss-in-weight feeder

Two different approaches to computing massflow are used. The most common strategy is to differentiate the weight on the scale system with respect to time as the earlier graph indicated. The first differential of weight with respect to time is massflow is a pretty straightforward calculation and is shown below.

$$MF = dW/dT$$

A different approach to massflow prediction is also possible. Why not integrate a massflow value computed from a prior weight loss to predict a new weight value at time "T". As an example, the equation for predicted weight in the next time interval could be written as:

$$\text{Predicted weight } (t+T) = \text{Prior Weight}(t) - MF*T.$$

where T = the sample time period or interval

Deviations of the predictions from the actual measured weight value result in a modification of the massflow estimate and a new future weight prediction. A software implemented filter called a Kalman filter that uses statistical mathematics develops the prediction.

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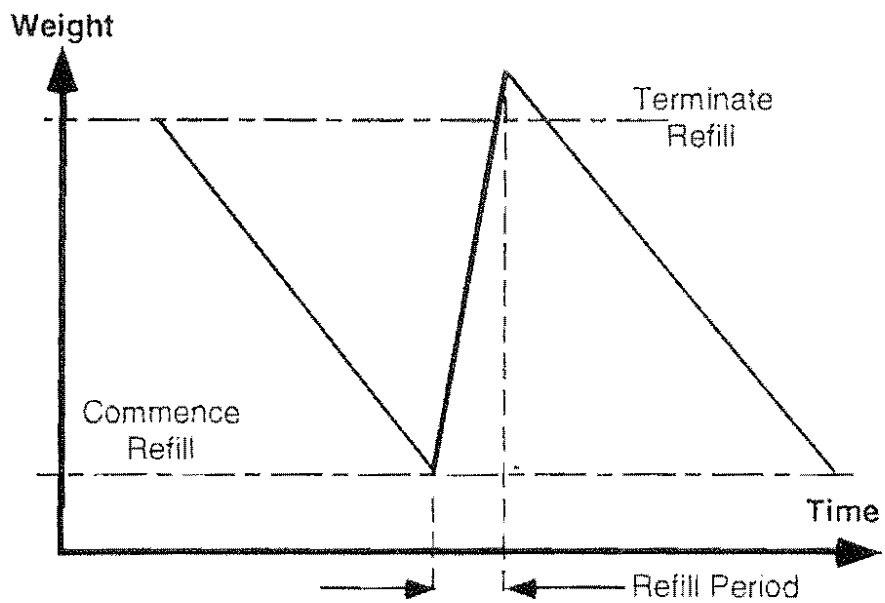
The refill process

While the feeder is operating in gravimetric or mass control, the weight loss is being detected and if not meeting the desired value of setpoint, corrective actions to the metering device occur. However, the feeder process, while it uses a direct measurement of weight, is discontinuous in operation or at least its measurement process is. That is, if the feeder continues to operate, the weight of material in the feeder hopper finally is exhausted, resulting in no flow to the process. To overcome this operational flaw, at some point before the feeder hopper becomes empty, a refill of the feeder hopper is required. The feeder is not permitted to stop its discharge however, so the refill must happen " on the fly". Two methods exist to refill the feeder hopper; manual method by the operator and the automatic method using machinery. Manual refill implies that a bag of bulk solids is tossed into the feeder hopper and the process continues. Automatic refill implies that machinery under control of the feed system will add material to the feeder hopper from an upstream supply. We will focus on the automatic approach since the manual approach to refill is merely looked upon as a large scale disturbance and is basically ignored by the control system.



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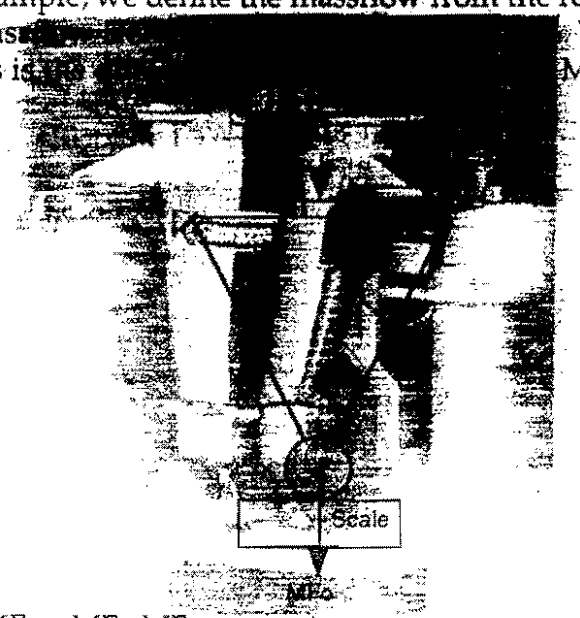
The refill process, con't

In automatic refill, the feeder control system switches to volumetric control, which means the feeder discharge velocity is fixed for the duration of the refill process. Why? The problem is a classic algebraic dilemma. We have one equation and two unknowns.

When in normal operation, with only weight being lost from the scale system, the weight loss over time represents the massflow into the process. When refill occurs, the scale measurement includes both the in-feed from the refill system and a discharge from the scale mounted vessel.

For this example, we define the massflow from the refill device as MF_r and the mas[illegible] What the scale determines is [illegible] MF_s.



therefore $MF_s = MF_o - MF_r$

Neither MF_o or MF_r are known independently. Therefore, we calculate neither during refill and lock the feeder output. Is there a way around this situation? What might be the result of continuing in gravimetric control while refilling? Likely the metering device would operate at full speed. Why?

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Improving the refill process

It is easy to see that it is possible that the massflow can be in error during the refill process. Due to various influences on the material, the metering device, when the feeder hopper is nearly empty, may have a velocity component somewhat greater than it had when the hopper was full of product. Often that velocity may be higher by more than 10%. Why? What does this mean to the massflow as the feeder completes its refill cycle? The massflow rate may be high by as much as 10% immediately after refill until the system returns to the gravimetric mode and re-establishes control.

This process can be corrected to some degree by preventing the material level from getting too low in the feeder bin. Or the Refill Array® may do the trick. The Refill Array® monitors conditions as material is metered from the feeder and applies that information to the feeder control during refill to compensate for any changes in output. Since operation of the array is based upon history, perfect flow control during refill is unfortunately not possible but often times, much better results are found than when the feeder output is merely locked to a specific velocity. This technique is particularly helpful when refill times are long. Normally, you should try for a refill period of about 6 to 10 seconds. This insures positive control over the incoming material but is short enough in duration that minor flow variations should not perturb the downstream processes.

Disturbance detection

Disturbance detection is critical to the operation of both a derivative and integrated massflow computation approach. If a disturbance goes undetected, the massflow calculation is impacted by that disturbance. There are a number of concepts in disturbance detection. Some will use the second derivative of the weight value, others might use a comparison of expected weight to measured weight as the trigger. What is done after disturbance detection also varies. Some lock the output of the controller when a disturbance is detected. Others may use stochastic control concepts to dynamically change filtering constants. Each vendor tries to limit the amount of output discontinuity due to outside weight disturbances.

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Benefits of using loss-in-weight feeding

Loss-in-weight feeding has many benefits and few disadvantages. Among the benefits are:

- The optimum feeding device may be selected for material to be fed.
- Material is fully contained, keeping your work area clean.
- Calibration accuracy is normally a function of the weighing system only.
- If refill period is short, a high level of control is achieved using actual measurements from flow.
- High accuracy over large setpoint turn-down values is possible.

Loss-in-weight feeder compromises

The major problem with loss-in-weight feeders is a problem of discontinuity. What I mean is that the feeder can't run in gravimetric control all the time because at some time in the period, the unit has to refill. The feeder controller switches to volumetric control where rate calculation is suspended. The feeder can't control its flowrate when it is uncertain what the real weight loss measurement is. Essentially, the speed of the discharge device is locked (volumetric control). Why can't the feeder stay in gravimetric control during refill? Is there a way that it could? Also, the issue of scale resolution and sensitivity to vibration is a factor in accurate weighing using this technique. As setpoints become smaller, the need for a high quality installation, minimal plant vibration, and air currents, etc. must be given more serious consideration. For large flow rates, having adequate vertical space becomes a serious issue.

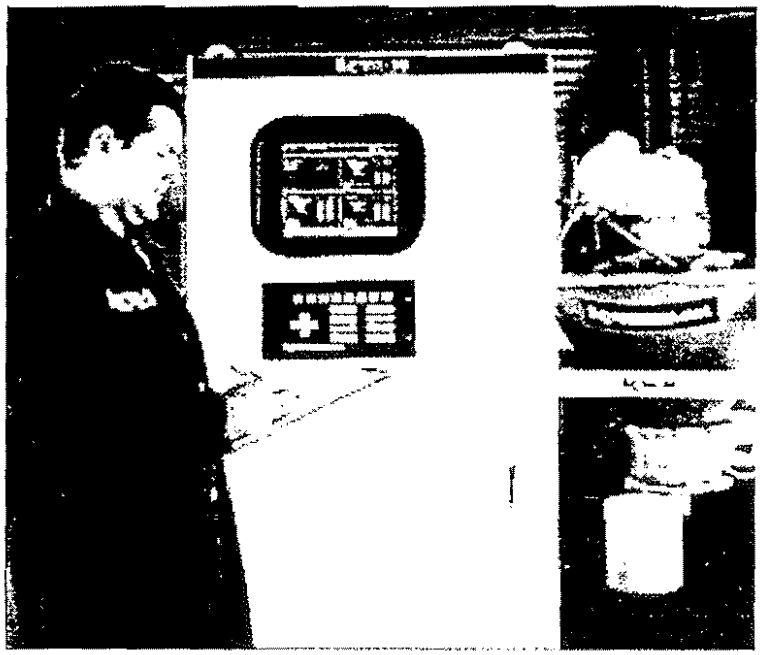
Loss-in-weight feeder applications

With the correct feeder involved, these types of gravimetric feeders can feed a variety of materials from flow rates below 1 kg/hr to rates higher than 5000 kg/hr. These feeders handle pigment, resin, and other special bulk solids used in compounding with good accuracy.

Feeder Control Systems

Introduction

Feeder control systems have moved away from analog and even simple digital systems of the past. Now most feeder control systems use one or more microprocessors and related hardware to control the flow from a gravimetric feeder. This section will briefly describe current concepts in feeder control. Here is a picture of an example of a multi-unit feeder control system with color monitor.



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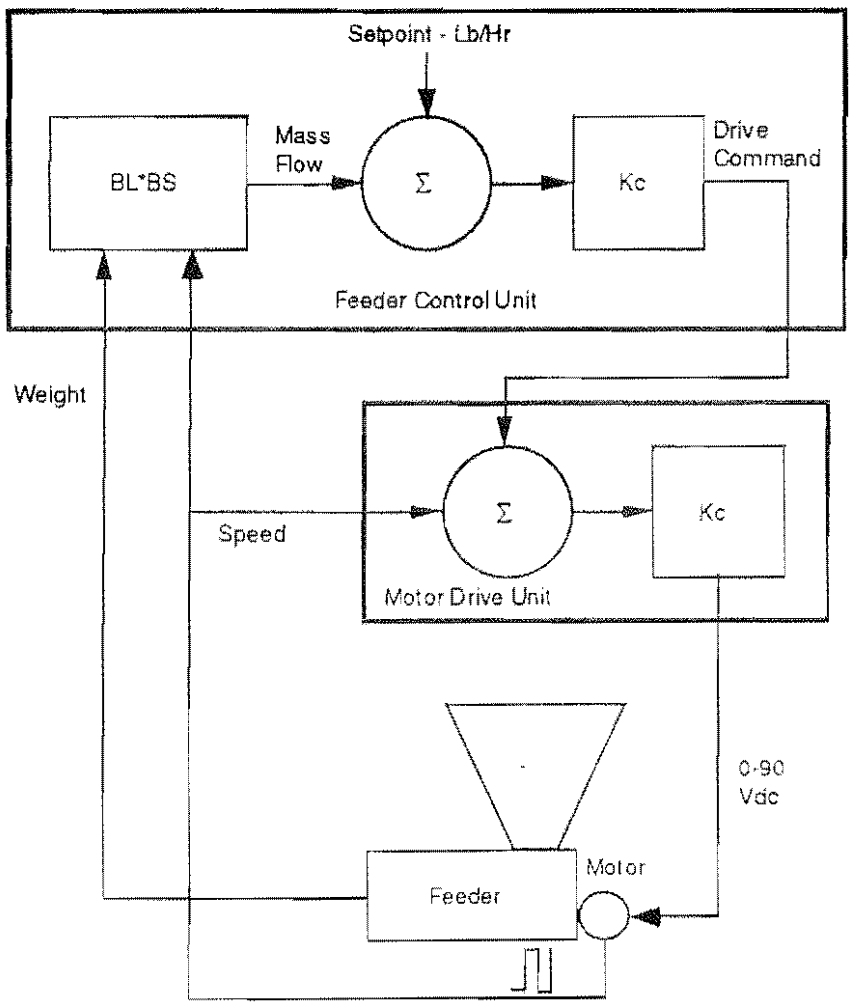
Weigh belt feeder control system

The typical feeder control system is really nothing more than a conventional PID control structure with a special front end to handle the conversion of weight data and possibly belt velocity into the process variable signal called massflow.

Weigh belt feeder controllers tend to be quite simple. The computation of massflow from belt velocity and belt loading is easy. Complexity comes from handling I-O activities, the user interface and communications to the outside world of plant computers. Here is an example of the weigh belt control system.



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Weigh belt feeder control systems, con't

In the prior example, cascade control with the measured variables of weight and motor speed are used to compute belt loading and belt speed. When those two values are multiplied, massflow is the result.

Loss-in-weight feeder control system

On the other hand, loss-in-weight controllers tend to be more complex because of the nature of the way in which they must convert the process weight information into massflow data. There are a number of ways to go about the conversion process. First, and probably most challenging is the determination of what the real weight value is that is measured by the weight sensor. The controller needs to remove all weight influences except the actual weight loss of the material to produce an accurate massflow value. Noise on the weight signal created by vibration of the plant, motor and other mechanical noise requires the need of sophisticated strategies to eliminate them prior to the massflow calculation.

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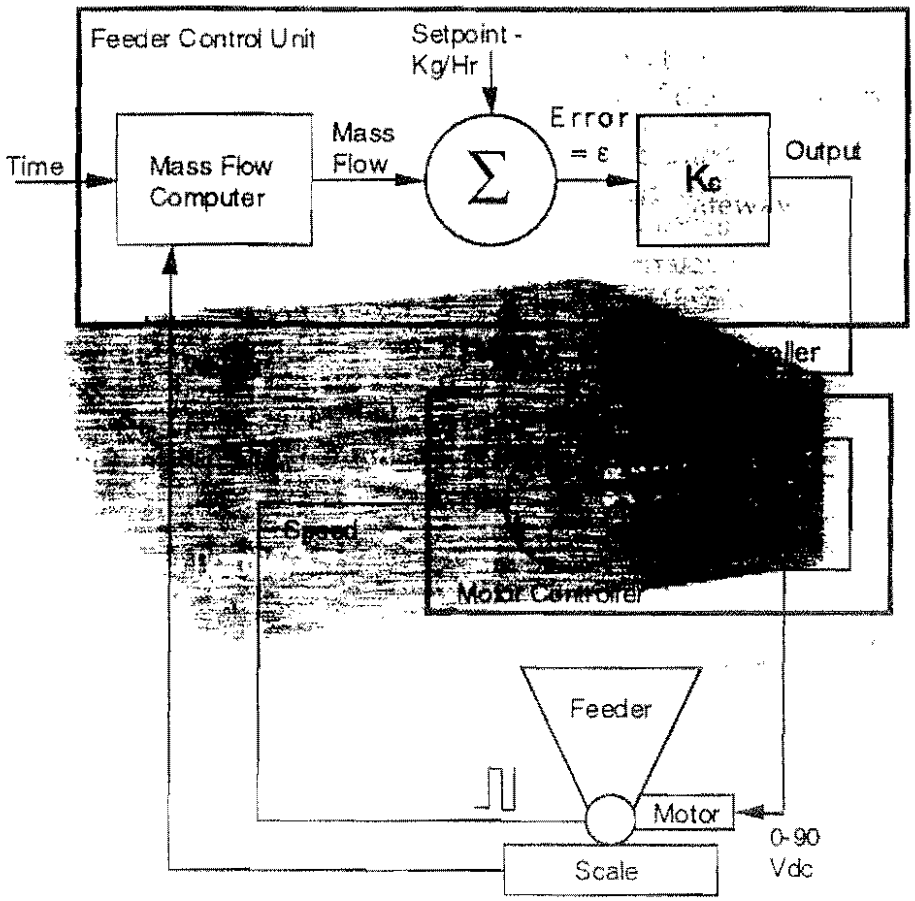
Loss-in-weight feeder control system, con't

Here is a diagram of cascade control in a loss-in-weight feeder control system.



In this example, weight and time are computed as discussed and the result is in massflow units. Comparison to setpoint with appropriate corrective action being taken if the massflow and setpoint are unequal. Sophisticated filters such as the Kalman technique and Digital Signal Processing -DSP - are becoming more common in an attempt to compute a more valid massflow value. This is the real issue in high performance loss-in-weight feeder systems.

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The user interface

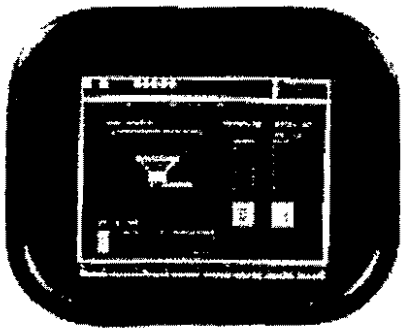
The user interface of many microprocessor based feeder control systems include either a multi-line display or a CRT monitor, either monochrome or in color to enhance operator effectiveness in using the control system. Keyboards of various configurations are used in feeder control systems. Single and multi-user stations can be found from nearly all manufacturers. Every vender tries to provide a unique and optimal solution to the user interface question.

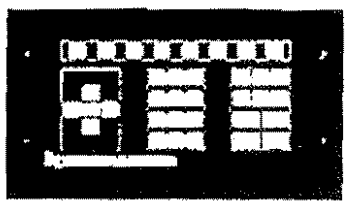
Here is an example of a typical single ingredient feeder control panel. This is a K10S control panel from a K10S chassis controller.

Continued on next page

The user interface, con't

Next is an example of a multi-feeder system user interface that uses a color monitor for information display. This interface is called the K-Commander and provides recipe storage, 4 process line control and communications to a host environment. English, German, French and Spanish are supported display languages.





I like to see simple user interfaces. From an operational standpoint, I believe that designers should use the power of the computer inside to make the user interface simple on the outside. Interfaces should provide clear, unambiguous messages, tell the user what to do in simply understood terms and provide direction that results in no operational error by the user. They should be intuitive to use.

In the least, messages and key descriptions should be either universal where practical or in the users language where a universal description is not precise and clear.

There are both good and poor implementations of user interfaces. The user public must decide what is important and direct their vendors to an implementation that suits them..

Current Feeder Design Strategies

Introduction

This section deals with current trends in feeder design for compounding applications.

What's new?

Feeder vendors know that compounders are faced with a problem that is similar to those faced by manufacturers of discrete products. Unlike earlier times, process runs are smaller and more variations are required in the delivered product. Rapid product changeovers are now the norm in many locations. Compounders are faced with the need to produce short runs of product with rapid clean-up and changeover to a new product and new formulation. The problems are many. I can list some of them here.

- Feeder cleaning, how easy?
- What about calibration?
- Will the new material feed correctly in the feeder I have?
- How fast can I make the changeover and how difficult is it?
- Do I have to re-program my feeder control system to feed a new material?

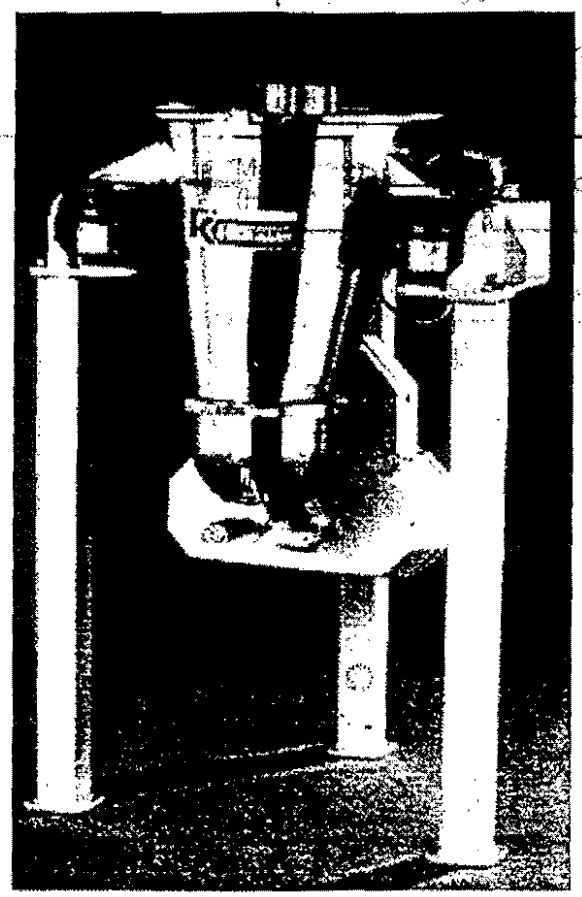
I believe that modular feeder systems, that is, feeder systems with removable metering units that can be rapidly interchanged or removed for cleaning, are the way of the future in compounding. Modular designs permit rapid cleaning of the feeder portion, quick and easy changeover from one feeding module to another with no re-calibration, since the weighing system is left undisturbed.

Continued on next page

The **modular** feeder.

A typical modular loss-in-weight feeder will permit exchange of the feeder unit to best suit the application. A twin screw discharger can be replaced with a belt feeder, a single screw feeder or a vibratory tray feeder to meet a wide variety of feeding needs. The modular feeder should be designed for easy cleaning and for rapid product changeover.

Here is an example of a smaller modular loss-in-weight feeder using a twin screw discharger for feed rates up to 100 Kg/Hr. Notice the removable feeder section at the bottom.



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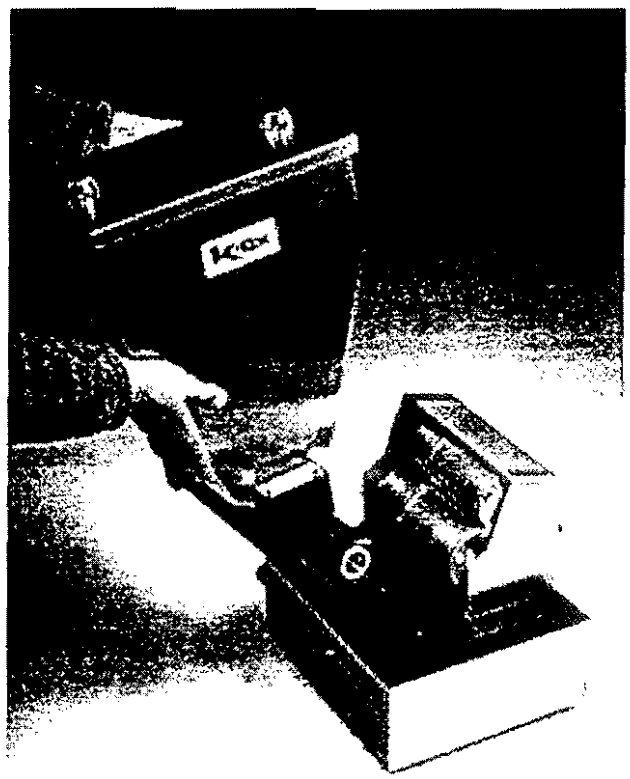
Compact feeders

Additionally, some vendors have begun to recognize the needs of the experimenter and laboratory user. Venders may now supply smaller and less costly equipment for those in the R&D and product development environments. K-Tron has the compact feeder line which uses small, accurate 24 Kg scales to support three different types of feeders in loss-in-weight configuration depending upon need. Shared controls reduce cost further. These feeders are small, designed for low rate feeding and allow grouping around an extruder port.

Here, as an example, is a small single screw feeder on a 24 Kg scale designed for laboratory applications or low rate applications. Note the removable hopper assembly.



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The modular control system

I also see the control system becoming modular as well so that you buy only the control pieces that you need and only plug in advanced capability when necessary. Software driven instruments and controls permit such action. It also provides for easy upgrades and product improvements.

Some vendors are providing feeder control capability in a PLC I-O rack. The feeder control system is imbedded in the users PLC network and system. This is an approach to modular control.

I also suggest that with the current state of electronic design, reliability for well cared for equipment is high. With improved software design techniques, the integrity of the software which controls the operation of the feeder control systems is becoming more robust.

To study modular control systems, we have to examine a topic called local area networks and supervisory control.

Supervisory Control

Overview

Introduction

This chapter will show what is currently being used today in control systems for supervisory control with specific discussions about feeder control systems and their link to the plant-wide control system.

In this chapter

We will cover the following topics in this chapter on supervisory control.

Topic	See Page
Supervisor to Feeder Communication Links	45
Local Area Networks	48
Proprietary LANS	55

History of supervisory controls

In the early days, analog information was transferred to and fro to controllers and supervisory computers. In most plants today, computerized information is transmitted on electrical cables from sensors and controllers to supervisory computers. We will leave the exact evolution to others. Let's look at a current approach of sending data by serial means.

Supervisor to Feeder Communication Links

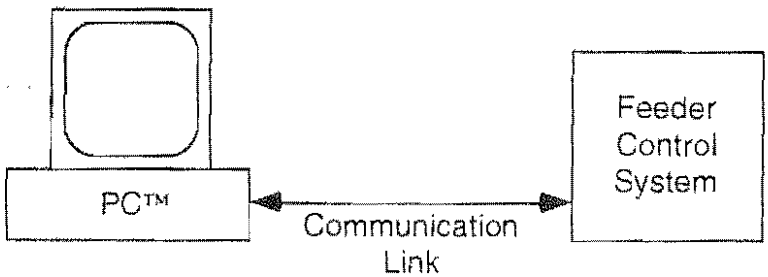
Introduction

This section outlines some common strategies for linking feeder systems to a host supervisor.

Supervisory link using a PC

Computer based control systems have made it extremely easy to connect to all sorts of external embedded microcomputer systems. One can use a PC to communicate to a feeder system using icons on the PC screen to define a control implementation.

Such a control system is shown next. Communication is often times handled through an ASCII serial data link.



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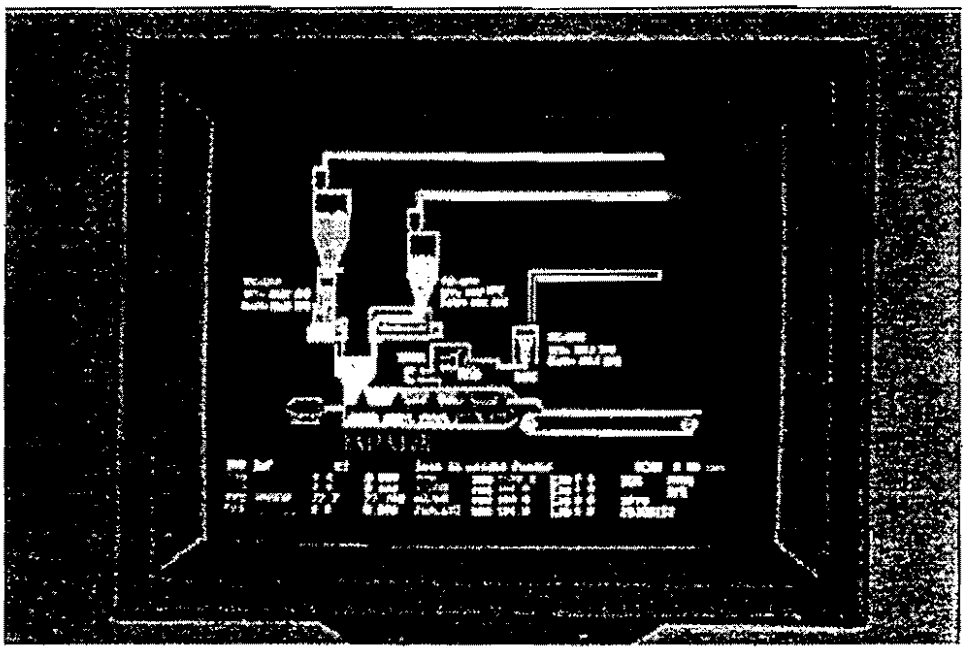
Supervisory link using a PC, con't

This photo shows a representation of a compounding process on a PC monitor. Data retrieval and presentation is controlled by the application program in the PC



Recipe storage, flexible alarm and data tracking systems can all be implemented with relative ease.

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PLC/DCS supervisory links

Also, many feeder control systems connect to nodes or gateways on a data highway such as those from Modicon and Allen Bradley. These devices connect between the feeder control system and the PLC.

Users have many choices in how to interconnect the feeder system to the plant-wide control system for the passing of data and control over serial data channels.

This picture is of a typical feeder control system gateway.

The PLC and the feeder control system connect to such a gateway which converts the PLC language into one understood by the feeder controller and in reverse, the gateway converts the feeder control language into a syntax understood by the PLC.

In a future graphic, a network will be drawn that shows this gateway in use. This leads us to discuss, in general terms, local area networks.

Local Area Networks

Introduction

This section will introduce the concept of networks and discuss some of the more common ones.

When it comes to networks, a designer has a lot to do. The medium over which data movement will occur as to be defined. The topology or organization of the network has to be characterized. The access strategy has to be implemented and the message syntax and protocol has to be established. There are also other issues such as real-time considerations.

Local Area Networks, LANS, the preliminaries

All of the prior work culminates in local area networks. "Data highways" are a form of local area network. While there are twisted pair, optical fiber, broadband, baseband and carrier band strategies that define today's local area networks, other references are suggested for information on the detail of these concepts. Topology, or the organization of connections also fits a number of concepts: the ring, the star and the bus. The principle standards in defining access strategies for networks are IEEE802.3 for Carrier Sense, Multiple Access with Collision Detection(Ethernet™ designed by Xerox at PARC was the basis) , IEEE 802.4 for Token Passing Bus Access Method and IEEE 802.5 Token Ring Access Method. ISA Proway-SP72.01 -LAN standard is a restrictive form of IEEE 802.4 designed for industrial use. Many other LANs exist. ARCNET, PC Net and StarLan are among them.

Plenty of PC LANS also exist. Novell is one producer. Banyan is another. Vendors tend to proliferate as technology moves forward.

We now study an ISO-OSI standard in 7 layers that is becoming a driving force to consolidate network structure and function.

Continued on next page

ISO-OSI network model

The ISO-OSI Open Systems Interconnection reference model is an effort to define a standard for all computer communication schemes. It is a 7 layer model.

User Layer
Program - Layer 7
Presentation - Layer 6
Session - Layer 5
Transport - Layer 4
Network - Layer 3
Data Link - Layer 2
Physical - Layer 1

The User layer is the application that uses the network. The Program layer provides the communication link between the network software and the user software. The Presentation layer handles the necessary re-configuration of data in and out of the network. It might convert ASCII data to EBCDIC. The Session layer controls the data flows in and out of the network. It also synchronizes activities on the network. The Transport layer provides data transfer from node to node on the network. The Network layer handles routing of messages between non-adjacent nodes on the network. The Datalink layer reduces error rate issues when messages move between adjacent nodes. A number of IEEE standards such as IEEE 802.3 defines operation of the Data Link layer which involve providing access. The Physical layer codes and transfers data between adjacent nodes on the network. There are ISO specifications that define each of the layers.

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Network transmission media

The transmission media is in three domains: Broadband, Baseband and Carrier Band.

Broadband is a transmission medium that has many carriers on the bus, frequency multiplexed to provide channel separation. Think of how cable TV works. Multiple channels, each carrying data from transmitter to receiver. Bandwidth for an electrical cable system using 75Ω coax is about 350 MHz. Significant data can be transmitted on a system with this large bandwidth.

Baseband transmission is done by time spacing digital signals, one at a time, on a bus. One often thinks of digital pulses traversing from 0 Vdc to +5 Vdc as a form of data that you would see on a baseband system. There are other versions such as +/0/- levels giving three states rather than two. Twisted pair, or more often coax, is the cable choice. To work correctly, baseband is used in point to point communications, in a bus arrangement or in a ring topology.

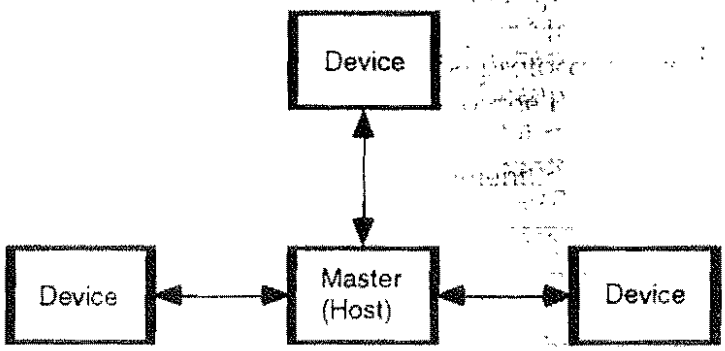
Carrier band uses a single rather than a multiple carrier of the broadband system. In many ways, it is a single channel broadband system. It is often found in industrial environments.

Continued on next page

Network topologies

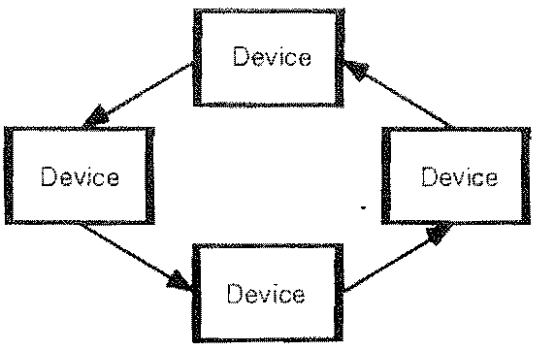
Network topologies describe how a device connects to others to which it must communicate. Network topologies generally come in three versions. The Star, the Ring and the Bus. Diagrams show the concepts. You can also have combinations of each in a system.

If the Star Topology is used, it is built around a central control point. In the early days, a central computer was at the center, terminals at the points.



The Star Topology a key concept when master/slave communications are used. This concept does not permit peer to peer communication except through the host. Star topology works like your phone system in your home.

The Ring Topology supports peer to peer communications.



Each communication device in the ring sees all of the data passed in the ring. It is possible that if a single device fails, the total network can fail.

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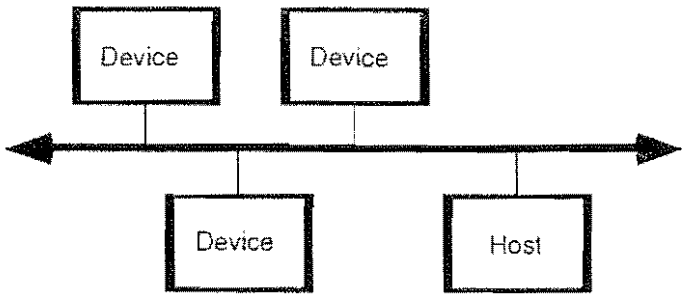
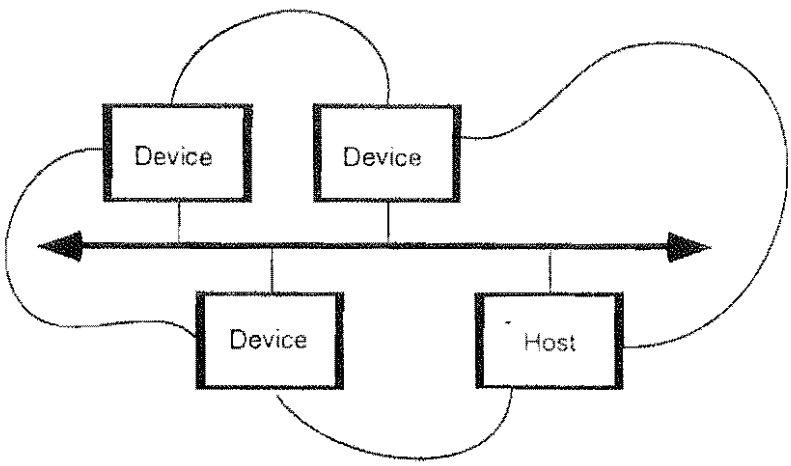
Network topologies, con't

The Bus Topology looks like an extended computer bus. Devices connect to the "backbone". Peer to peer communications is supported.



It is fail-safe in the fact that if any device fails, it will not likely shutdown the network. The AC power wiring in your house is set up much the same way.

Today, many local area networks will use a combination of topologies to best fit the network to the problem at hand. I should also point out that what has been described as a physical topology can also exist in a logical topology. That is the physical bus topology can exist as a logical ring topology as shown below.



The curved lines indicate a token being passed in ring fashion from one node to the next even though the devices are on a bus.

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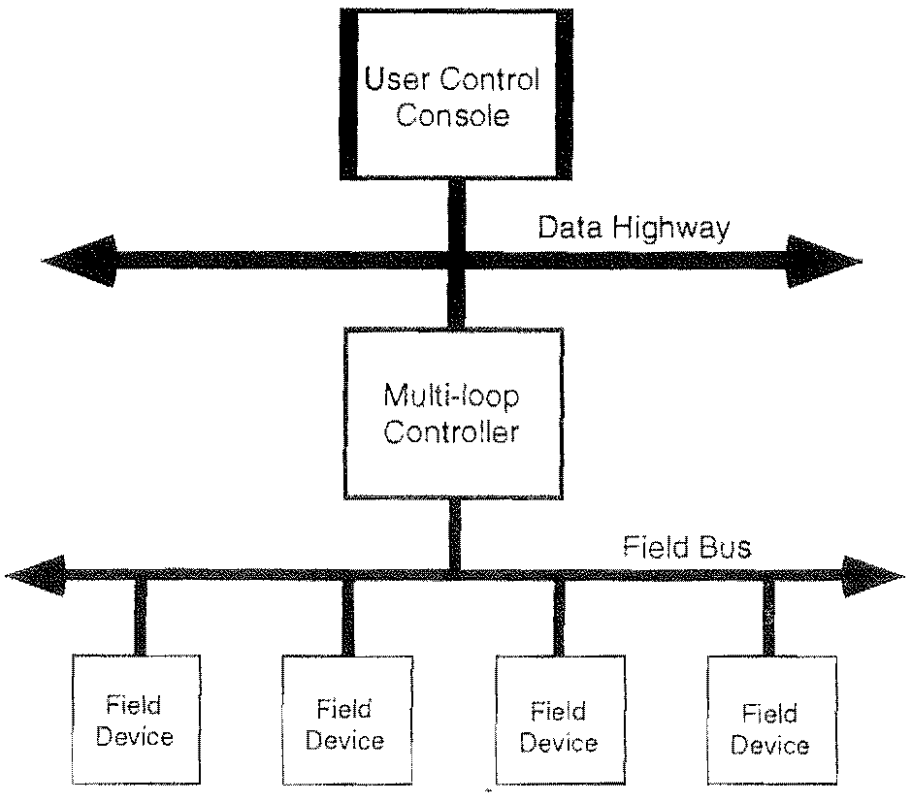
Field bus

Field bus is gaining acceptance in the United States. Two versions of field bus are used in Europe. Those field bus applications are "Profibus" and "FIP" first converted into ISP and WorldFIP and now joined as the FieldBus Foundation. When ISP and WorldFIP were independent, they were incompatible. As the Fieldbus Foundation, they have become joined. Additionally, a separate standard from ISA and IEC called SP50 Fieldbus may soon be a reality. DeviceNet from Allen Bradley may become common for simple field devices. A diagram is shown to indicate how fieldbus might be used.



Field bus will likely replace most applications that once used a 4-20 ma signal to send data from the field to the control system.

Continued on next page

MAP	The Manufacturing Automation Protocol-MAP implements the International Standards Organization Open Systems Interconnection model as a network and more. It is a broadband network using IEEE 802.4 bus with impedance matched drops. It is a token passing bus. It is primarily used in discrete manufacturing and was initiated by General Motors in 1980.
TOP	While General Motors was the major proponent of the MAP protocol, at about the same time Boeing created TOP - Technical and Office Protocols. The Boeing model uses CSMA/CD model in carrier band medium. The reason that this protocol was selected was that messages in the office environment were likely small and that with light traffic, rapid response is possible. GM and Boeing have joined forces to bring MAP/TOP to users. Presently the focus of these strategies is to aid discrete manufacturing and is not the major focus of industrial control. Time will tell if this model can overcome the strength of the other data communication protocols on the market.
TCP/IP	TCP/IP or Transmission Control Protocol/Internet Protocol has over a million nodes and many more active users. This active network evolved from the US DOD ARPANET. This network has its focus in the academic and research world and is used in plants as a general purpose network where UNIX is locally used as an operating system.

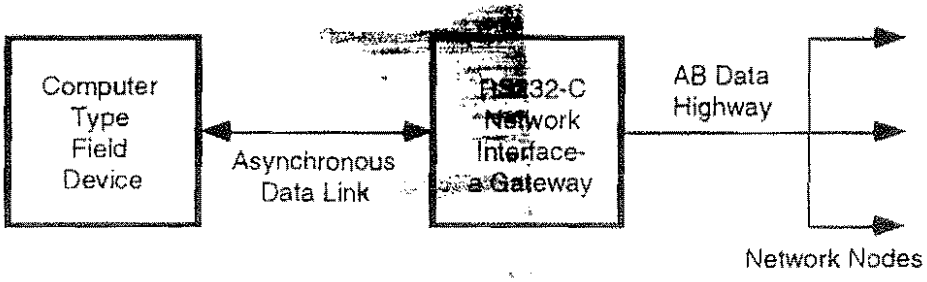
Proprietary LANS

Introduction

This short section will take a peek at some more commercial proprietary methods of data communication. Many feeder vendors use a proprietary method of external communication. This means that gateways and other protocol converting techniques are needed to convert the "feeder control language" to a language or script recognized by the supervisor.

Allen Bradley Data Hi-Way™

Allen Bradley's PLC communication path is a local area network that permits peer to peer communication to 64 nodes (addressing is octal). A modified token, half duplex polled protocol is used at 57.6 K baud. Data Highway Plus™ is similar but its purpose is to link PLCs together in a compact system. The feeder control system is the block on the left.



Two types of messages - in packet form - are sent on the network. Protocol bytes as Allen Bradley calls them are designed to get the data to where you want it to go. Data bytes is the data included in the message. Most Allen Bradley PLCs can read and write messages. send commands and issue diagnostics.

Continued on next page

Allen Bradley Data Hi-Way™, con't

Next is a sample of a typical message packet that is sent by the Allen Bradley PLC.

DST		CMD	STS	TNS	DATA

The following are the syntax used in this message.

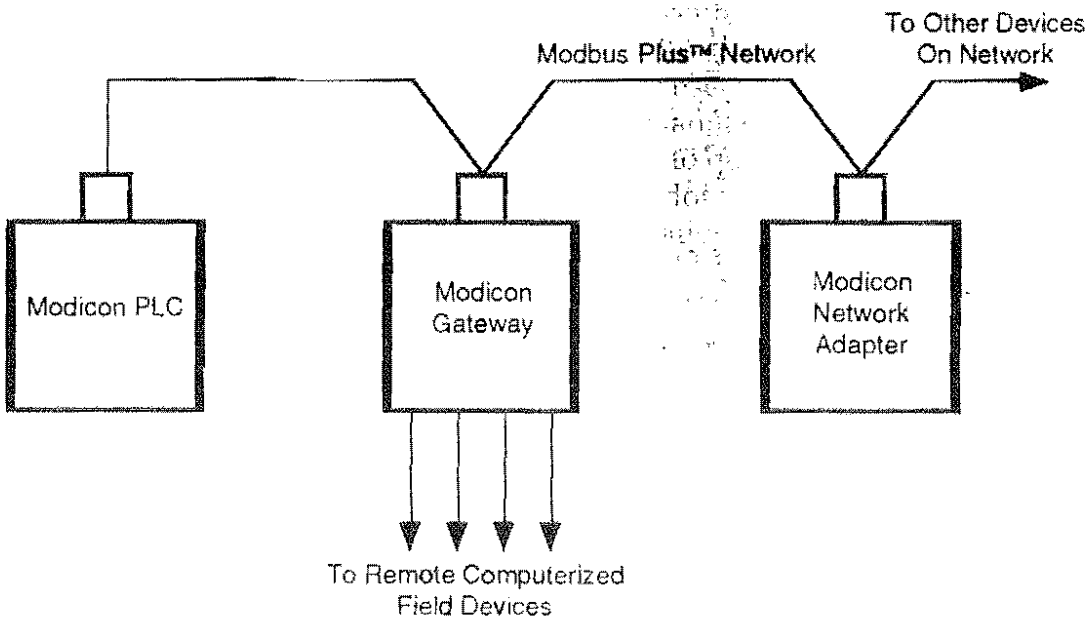
DST = Destination node for the message
CMD = Command code
STS = Status code
TNS = Transaction number (2 bytes)
Data = Data

This message format is one of a couple used. Full duplex messages are different.

Continued on next page

Modicon Modbus™

Modicon's communication link for connecting devices together on its local area network is call Modbus™ or Modbus Plus™. The following graphic shows how certain devices might be connected. Feeder control systems are connected to the Modicon Bridge/ Multiplexer. Up to 32 nodes (addressing is decimal) are possible to attach to the network. Much like the Allen Bradley system, this network uses token passing to provide a time deterministic specification. However, the two networks are incompatible.



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Modicon Modbus™, con't

Next is a sample of a typical message block that is sent on the network.

PRE	FLAG1	ADDR	FIELD	CRC	FLAG2

Definitions:

PRE = Preamble
FLAG1 = Opening flag
ADDR = Address of receiver
FIELD = Data
CRD = Cyclical Redundancy Check
FLAG2 = Closing flag.

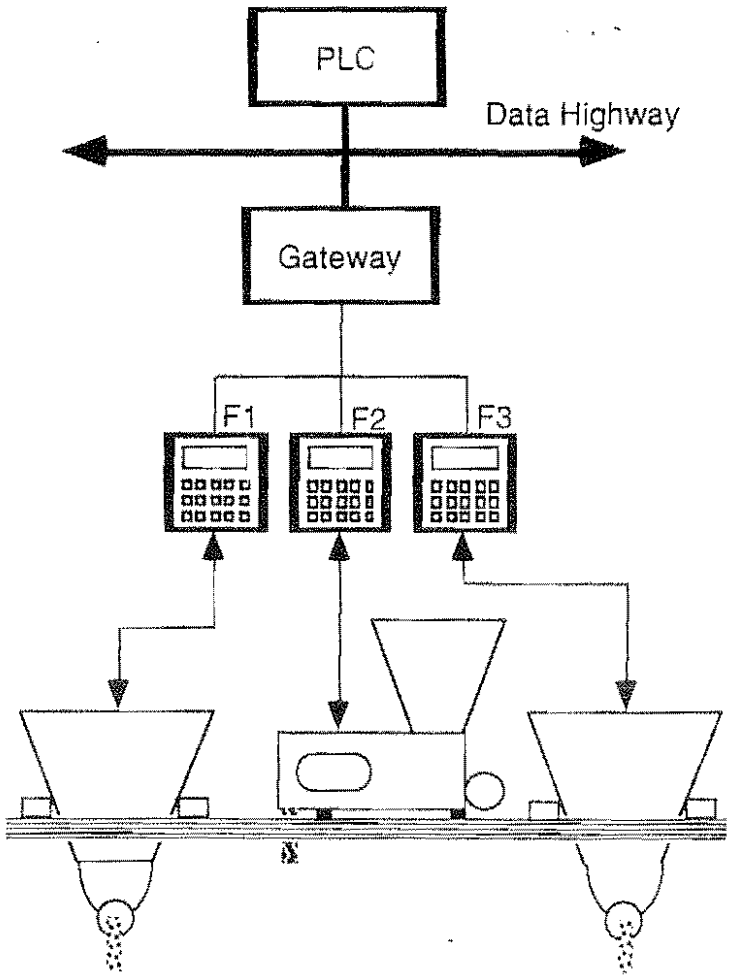
As you can see, a lot of thought goes into describing a specific protocol to work in an industrial environment.

In building a communication link between your feeders and PLC can be daunting when you have to deal with these kinds of issues.

Continued on next page

K-Tron's data link

This is a picture of how a typical feeder setup of many controllers might be connected to a host machine. The PLC is the supervisor. A gateway converts the network token passing scheme to asynchronous data transmission to be used by the feeder system. K10S chassis controllers are shown here.



In the above picture, the PLC or the K-Tron system must have a software solution to convert the message format from PLC to feeder controller and back again.

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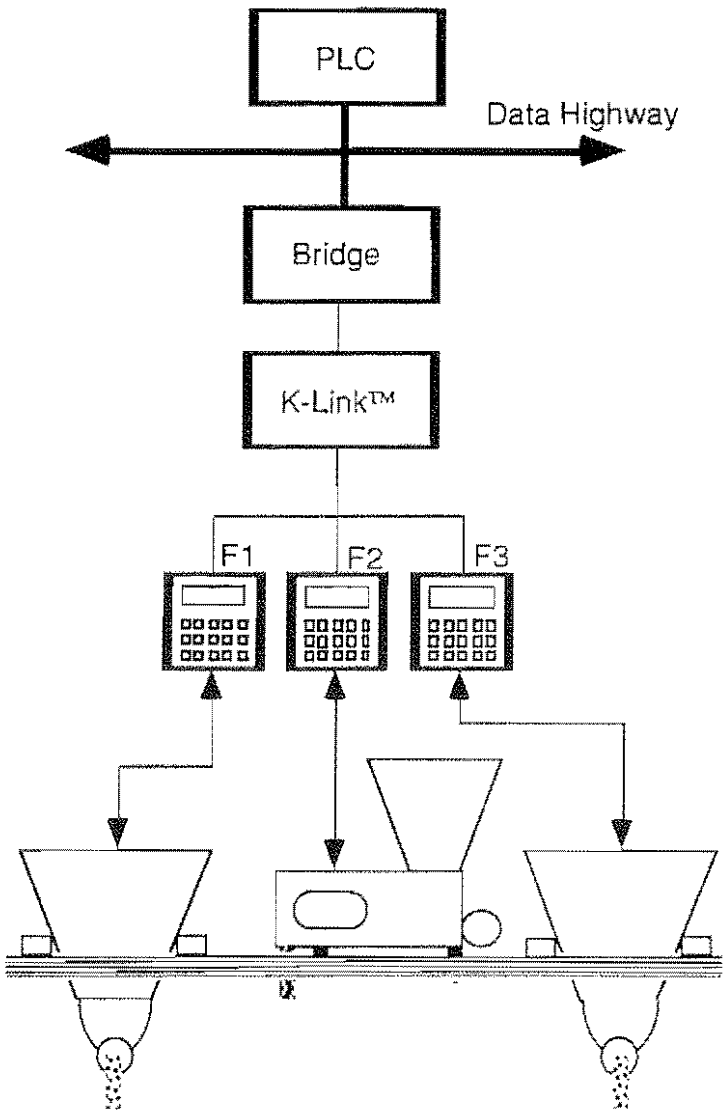
K-Tron's data link, con't

The next diagram shows the addition of K-Link™, a special protocol converter, an electronic box, that eliminates that need. We can consider the bridge and K-Link™ together as a full gateway.



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K-Tron's data link, con't

If you were using a Modicon PLC, the data highway is called Modbus™. F1-F3 are feeder controllers operating the feeders shown. Data in K-Tron's format is sent between the feeder controllers and the K-Link™. Data in Modbus™ format is sent from the K-Link™ via the bridge to the PLC.

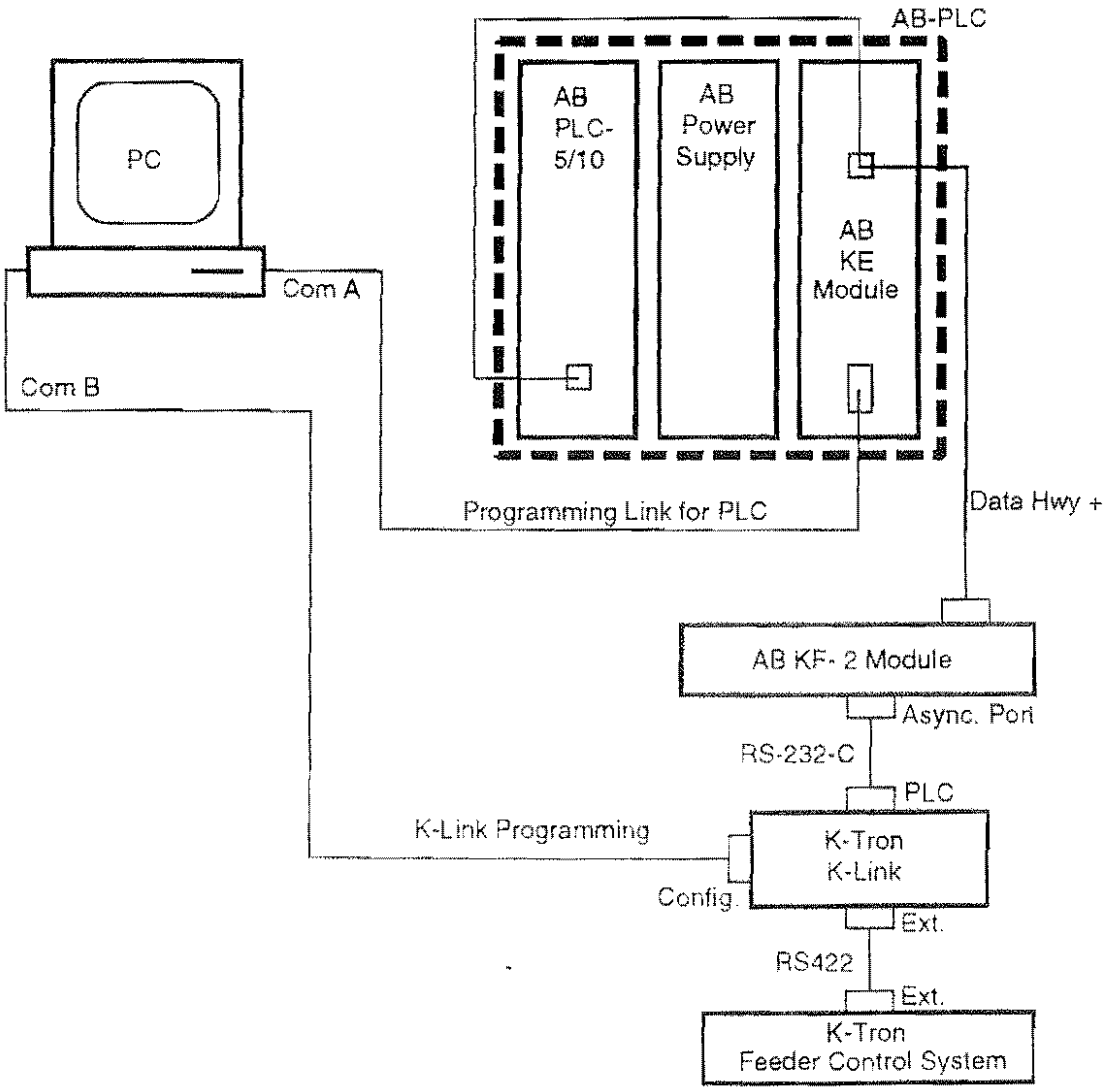
This diagram is a typical example of current state of the art in data communication in a feeder environment. However, some equipment vendors have gone one step further and implanted their control system as a node directly on the Allen Bradley or Modicon network, eliminating the gateway and potential protocol converter. This, of course, is done with full concurrence of the PLC vendor.

Let's look at an actual wiring arrangement.

Continued on next page

Allen Bradley to K-Tron connection

This diagram is intended to show what is required to actually configure a communication system between a K-Tron control system and an Allen Bradley PLC. The PC can be removed when programming is completed and is replaced by a user station.



Controls and Connectivity - The Future

Overview

Introduction

We will attempt to put into focus the future path of communications, process controls and feeder controls specifically.

In this chapter

We will cover the following topics in this chapter on the future.

Topic	See Page
Intelligent Systems and Devices	64
The Future ??	67

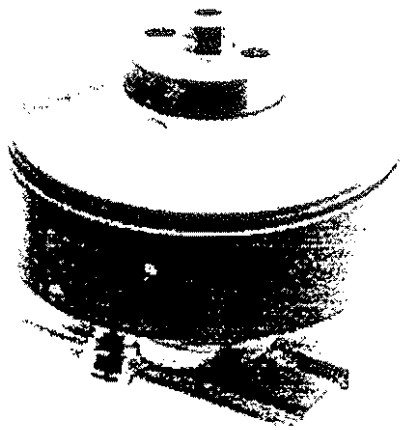
Intelligent Systems and Devices

Introduction

This section will propose a direction, one that is common to process control and then specifically to feeder controls. We will see how good the "crystal ball" is.

Smart sensors and I-O

With feeder control systems as a sub-set of universal control systems, intelligence is being placed at the point of usage. Simple controllers have microcomputers as a part of their construction. For example, microcomputers are built into motor drives to obtain precise speed control and diagnostics. The use of microcomputers permits sophisticated measurement, data transfer to the control system by digital data means and immediate control action. I-O modules and sensors are also "smart" devices and normally connect via serial means to the process controller. Such a device is shown below. It is a "smart" weight sensor. Its output is computer data in a message packet format.



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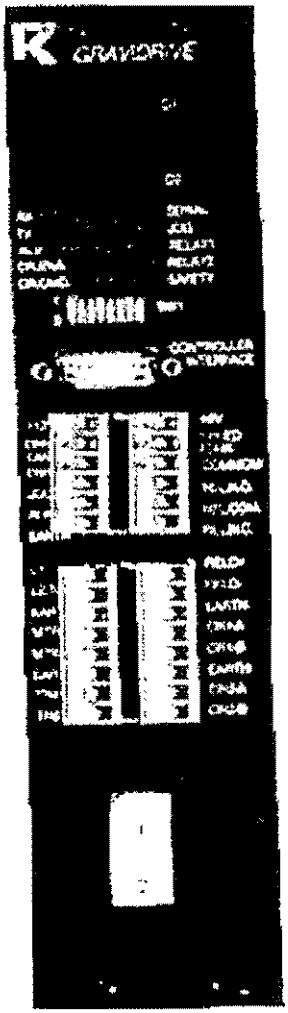
Smart output devices

Similarly, output devices will and have become "intelligent". Here is an example of a motor drive that is linked to a network.



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Standards in data links and control

Proprietary distributed control is being implemented at a rapid pace. This is causing a serious problem with regard to universal connectivity to devices such as sensors and alike. Proposals abound that deal with the issue of standards with the intent of common connectivity among manufactures of process equipment. For the process industry, fieldbus is a key. Standardization will likely be driven by feeder users who must connect feeder equipment to these networks. Presently, converters, gateways or routers, either external or built-in to equipment handle the message conversion are required with software written for the application loaded somewhere. You have already seen examples of gateways, bridges and routers.

Some work and pain must be endured to convert one data protocol to another to permit real data transfer and understanding. Likely, this will change as ISO and others develop some mechanism to handle the problems. Feeder vendors have to make the data translation process as simple and painless as possible.

Continued on next page

The Future ??

Introduction

This small piece attempts to predict the future in feeding controls and devices.

The future??

One always hesitates to predict the future. But to get a glimpse of what is happening in controls for general control processes, we may also see the future for feeder control systems.

The line that distinguishes PLCs from DCS from PC based systems is growing more fuzzy. Clearly PCs are being used more and more in smaller plants where low initial cost is key to acceptance. Hall Chemical in Wickliffe, OH recently installed PLCs and software running on a PC to automate their batch weighing plant. Smaller users will likely use this combination to make a conversion from a manually operated facility to an automated one. However, one has to question the robustness of a control system built upon a Windows™ overlay. Is the PC platform and the security of data communications adequate for meeting safety and performance standards?

Also, I expect to see a form of field bus ultimately become a standard for instruments mounted in the field. Fieldbus contenders, ISP™ (Austin, TX) and WorldFIP™(Research Triangle Park, NC) were recently joined as the FieldBus Foundation recognizing that a world standard is really that important. This means that intelligent measurement elements and final control elements will be interconnected via a standard network. True interoperability and interchangability of field components may be the happy result. We may return to the "old" days when instruments and controllers are again attached to the device they monitor and control. Unlike the "old days" links to the plant-wide network for coordination and supervision will be easy to implement, not in the manual way as in the past.

I believe that we will see more integration of products into each other as more alliances between vendors happen. PLCs imbedded in end products is not unusual, but specific application products imbedded in PLCs and DCS systems will become more prevalent.

Continued on next page

The future??, con't

Heuristics and the implementation of "fuzzy logic" will become more common in plants as process operation becomes more complex. Adaptive technologies are being implemented by engineers at many major processing companies to optimize their processes. Some of these techniques have been used with some success in feeder control applications. Simply stated alarms with clear and direct solutions presented to the operator or self-correcting strategies will be a common application of a rules based support system.

As we see controls becoming more flexible, feeders will become more flexible as the needs of plastics processors require shorter runs with a minimum of lost time during changeovers.

But as control and feeding systems become more complex and implementation issues more involved, vendor selection on issues other than price become more of a factor. The buying process should be based upon long term value. I suggest that you look for value in reliable, customer focused vendors for your compounding business as a way to hedge your bets for the future.

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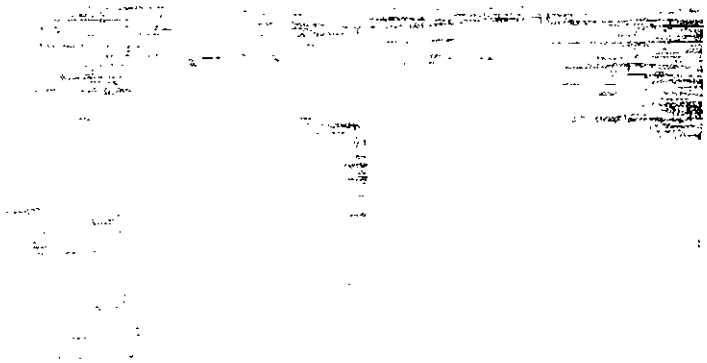
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