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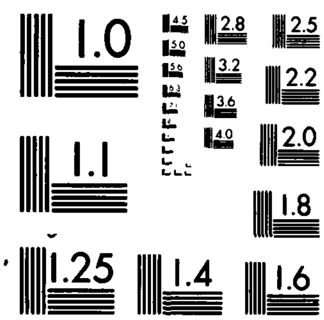

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PERFORMANCE STANDARDIZATION SUBCOMMITTEE,

AD A089831

13th MEETING MINUTES,

14-15 FEBRUARY 1980

(10) Henry F. /Hege

SACRAMENTO, California,

(15) N00024-78-C-5384

CHEMICAL PROPULSION INFORMATION AGENCY

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. CPIA Publication 321	2.	3. Recipient's Accession No.

4. Title and Subtitle
JANNAF Performance Standardization Subcommittee, 13th Meeting Minutes

5. Report Date
July 1980

6.

7. Author(s)
Henry F. Hege, Editor

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Johns Hopkins University
Applied Phys Lab--Chem Prop Inf Agy
Johns Hopkins Road
Laurel, MD 20810

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) N00024-78-C-5384
(G)

12. Sponsoring Organization Name and Address
Director
Defense Logistics Agency
Cameron Station
Alexandria, VA 22314

13. Type of Report & Period Covered
Meeting Proceedings

14.
14-15 Feb 1980

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This publication contains the meeting agenda, minutes and presentation materials from the 13th meeting of the JANNAF Performance Standardization Subcommittee. The main topic includes explanations and status reports on the Interim Solid Performance Program (Interim SPP) and associated program modules. Other topics include: nozzle flow analysis, space motor combustion spin effects, effects of expended inerts/slag, the BARF effect, particle impingement modeling, the Nozzleless Performance Program, thermochemical data, boundary layer analysis, vertical test measurements, and advanced performance methodology.

17. Document Analysis a. Descriptors

		SOLID PROPELLANTS
boundary layer analysis	performance analysis	spin effects
nozzle performance	performance calculation	SPP
NPP	performance prediction	thermochemical data

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement:	19. Security Class (This Report)	21. No. of Pages
Approved for public release; distribution unlimited	UNCLASSIFIED	~~382~~ 377
	20. Security Class (This Page) UNCLASSIFIED	22. Price [redacted]

(See ANSI-Z39.18) See Instructions on Reverse

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17. Document Analysis. (a). Descriptors. Select from the Thesaurus of Engineering and Scientific Terms the proper authorized terms that identify the major concept of the research and are sufficiently specific and precise to be used as index entries for cataloging.

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19. & 20. Security Classification. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED).

21. Number of pages. Insert the total number of pages, including introductory pages, but excluding distribution list, if any.
22. Price. Enter price in paper copy (PC) and/or microfiche (MF) if known.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CPIA Publication 321	2. GOVT ACCESSION NO. AD-A089 836	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) JANNAF Performance Standardization Subcommittee, 13th Meeting Minutes		5. TYPE OF REPORT & PERIOD COVERED Meeting Bulletin
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Henry F. Hege		8. CONTRACT OR GRANT NUMBER(s) N00024-78-C-5384
9. PERFORMING ORGANIZATION NAME AND ADDRESS Johns Hopkins University Applied Phys Lab--Chem Prop Inf Agy Johns Hopkins Rd, Laurel, MD 20810		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Plant Representative Naval Plant Rep Ofc; Johns Hopkins Rd Laurel, MD 20810		12. REPORT DATE July 1980
		13. NUMBER OF PAGES 382
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Commander Naval Air Sys Comd (NAIR-330) Washington, DC 20361		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

boundary layer analysis	performance prediction
nozzle performance	SOLID PROPELLANTS
NPP	spin effects
performance analysis	SPP
performance calculation	thermochemical data

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This publication contains the meeting agenda, minutes, and presentation materials. The main topic includes explanations and status reports on the Interim Solid Performance Program (Interim SPP) and associated program modules. Other topics include: nozzle flow analysis, space motor combustion spin effects, effects of expended inerts/slag, the BARF effect, particle impingement modelling, the Nozzleless Performance Program, thermochemical data, boundary layer analysis, vertical test measurements, and advanced performance methodology.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CPIA PUBLICATION 321
JULY 1980

JANNAF
PERFORMANCE STANDARDIZATION
SUBCOMMITTEE

13th MEETING MINUTES

14-15 FEBRUARY 1980

SACRAMENTO, CA.

CHEMICAL PROPULSION INFORMATION AGENCY
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The CPIA also provides technical and administrative support to the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee in accordance with DoD Instruction 5030.24, "Interagency Propulsion Committee (Army, Navy, National Aeronautics and Space Administration, Air Force (JANNAF))."

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PREFACE

This meeting, sponsored by the Joint Army-Navy-NASA-Air Force (JANNAF) Performance Standardization Subcommittee, is held annually to promote the exchange of technical information among governmental, industrial, and academic scientists concerned with the experimental measurement, analytical prediction, correlation, extrapolation, and flight confirmation of the performance of liquid and solid propulsion systems.

The meeting was held February 14-15, 1980, at the Red Lion Inn, in Sacramento, California.

Henry F. Hege
CPIA Representative

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Subcommittee Participants 371

Distribution List: 377

MEETING SUMMARY

I. The thirteenth meeting of the Performance Standardization Subcommittee was held 14-15 February 1980, at the Red Lion Inn, Sacramento, CA. Welcoming remarks were made by Dr Daweel George, AFRPL, Subcommittee Chairman. Mr M. Ditore, ASPC, served as Program Chairman and coordinated meeting arrangements. A list of attendees and the meeting agenda are presented in Appendices 1 and 2.

II. PRESENTATIONS. Reproductions of the slides and handout material from the meeting are given as Appendices 1 through 25 in the order that they appeared on the meeting agenda.

III. GENERAL MEETING MINUTES.

A. The Solid Performance Program. The current version of the program, known as the interim version, is operational, and documentation is forthcoming. Program objectives of predicting solid rocket motor delivered specific impulse within +-0.5% and thrust and total impulse with +-3% are being met for the test cases; however, a comprehensive program validation and verification are yet to be accomplished. The Interim Version SPP

(1) can handle different size particles with particle impingement,
(2) includes a new particle size model and drag law, a new combustion efficiency model, and a new throat erosion model;
(3) provides extensive plots and an expanded summary page
(4) Fully Coupled Transonic analysis (FCT).

Additional work is planned for the following modules:

(1) Grain Design and Ballistics
(2) One Dimensional Kinetics
(3) Two Dimensional Two-Phase Flow
(4) Turbulent Boundary Layer

(G. Nickerson)

A status report on the FCT subprogram indicates:

- that for REGION I, (throat entrance region) the calculations work well and are reasonably reliable;
- that for REGION II, (around backside of nozzle nose cap) the solutions are expensive and difficult to obtain.

These results indicate that the approximate transonic analysis should be used for parametric studies and the FCT for final performance prediction. (D. Coats)

A variety of Kinetic Rate data was presented for review. (D. Coats, M. Salita)

The SPP approach to combustion efficiency, involving dimensionless variables, was presented. The erosive burning options of the SPP were presented, along with the various modelling efforts in progress; and the problem of scale-up was discussed. (R. Hermsen)

The Grain Design/Internal Ballistics Module (GDB) contains four sub-programs: three-dimensional, two-dimensional and axisymmetric grain configurations and ballistics. The various features of the GDB and some examples of inputting various motor grain geometries were presented. (Appendix 9). (J. Lamberty)

The latest version of the SPP, the "Interim" SPP, is available now, upon written request to D. George, AFRPL. Requestors of the program should enclose a computer tape and state necessary tape specifications. The requestor will be provided with: a copy of the program, the thermochemical tape, sample case input and output, and a manual. Users are requested to offer feedback to D. George. The next, "1980," version of the SPP is anticipated to be available in the late fall 1980. (D. George)

B. One-Dimensional, Three-Phase, Flow Reacting Gas with Mass Transfer. A description of the various particle size change mechanisms which this program models was presented. Attention was focused on mass transfer. Presently, this mechanism is based on a single component species (AlO_2H) and should be based on multispecies. At present, there is no adequate set of screened reactions to go with mass transfer. It was recommended that additional studies should be conducted before including OD3P in the SPP methodology. (K. Hunter)

C. Experimental particle impact data, based on experiments now being conducted for the first time, were presented for review. Using a droplet generator, it is feasible to obtain experimental impact data in nozzle flows. (Z. Chiba)

D. The Space Motor Combustion Spin Effects include burnrate increase, increased slag, and change in Isp. Motor analysis uncertainties include particle density, particle size distribution, temperature gradient across the particle on the surface, effect of gas flow and temperature after particle deposition on inert surface, and particle propulsivity. (W. Brundige)

E. The effect of expended inerts/slag on performance may be taken into consideration by utilizing the three proposed definitions of Isp, expressed as: the propellant Isp, the delivered Isp, and the effective Isp. (J. Lamberty)

F. A description of the Burning Rate Anomaly Factor thought to be due to propellant flow during casting was presented. Common terminology includes BARF, hump effect and mound effect. (T. Kirshner)

G. The Particle Impingement Modelling discussion involved a review of work from several years ago, and included a call for more current work in this area. The smaller particles coated, and the larger particles eroded the nozzle. Impingement has an important effect on thrust losses and must be considered when designing an optimum contour. (W. Daines)

H. The Nozzleless Performance Program, currently under development at ARC, will address the phenomena of erosive burning, grain deflection, and combustion efficiency. Nozzleless motors operate at 65-85% of theoretical Isp--increased efficiency is obtainable by using propellants with low pressure exponent. In the erosive burning model, scaling effects must be taken into account. (M. Procinsky)

I. SUBCOMMITTEE STATUS. Annual report, accomplishments, current task areas, planned activities were presented. Appendix 19. (D. George)

J. Application of the constant fractional lag concept to kinetics and mass transfer mechanisms was suggested. The premise is that from the nozzle inlet to the throat various species lag by some constant fraction their equilibrium value at the throat. This approach would substantially reduce computer run time. The throat values would provide the initial conditions for full computation in the supersonic region of the nozzle where mechanism behavior has a significant effect on performance. A study should be conducted to determine the effect on performance prediction accuracy by application of this concept in the nozzle inlet region. (S. Cherry)

K. There is a need to establish a standard set of Thermochemical and Heats of Formation data and a methodology for distributing and keeping them current. (D. George)

L. Efficiency Definitions were offered as a set of equations. It was stressed that consistency of propellant specie input within equations and between programs is important. The "multi" Isp concept was discussed, i.e., delivered Isp, propellant Isp, and effective Isp. (D. Coats)

M. Boundary Layer Analysis. An improvement of Aerotherm's MEIT code was described, which is consistent with TBL, but has added capabilities. The MEIT shape factor should be improved. The code can handle rough or transpired nozzles, which TBL cannot. (M. Salita)

Aerojet is conducting a boundary layer analysis using a finite difference method, as opposed to an integral method, which was developed by Dwyer, University of California, Davis, and comparing results with TBL. (M. Ditore)

N. A method of Vertical Force Test Measurement was presented, with the observation that thrust vs time comparisons differ from horizontal to vertical testing. (R. B. Runyan)

O. Various aspects of Digital Filtering Techniques were described, including examples, techniques, and the effects of filtering. The caution was offered to beware of the interaction of test equipment with an experiment. Weighted averages may be used to smooth equipment oscillation effects. (R. Little)

P. A Three Dimensional Time Dependent Analysis was described. The application involved a rotating nozzle, rotating coordinate systems, and a chamber calculation with oscillating pressure waves. (J. Hoffman)

Q. A Static Test Panel--C. Beckman, M. Ditore, E. Landsbaum--was assigned to investigate performance measurements, to examine what performance parameters are currently being measured versus what parameters should be measured. The need was stressed for performance analysis and tests to present data in similar terms. See Action Item #5, p. 5 . (D. George)

R. Advanced Performance Methodology. The limitations of current predictive capabilities were enumerated, in part, and then followed by open forum recommendations to accommodate anticipated future needs. These are the ability to calculate, handle or more accurately predict the following:

- large shock waves
- gouging, uneven nozzle erosion
- particle size
- particle impingement effect
- distributed combustion effect
- more kinds of metals (Zirconium, Boron, Magnesium)
- 3-D grains
- multiflow ballistics
- occurrence of tin in zirconium
- high energy propellants
- temperature effect
- up to 300:1 area ratio
- nozzle submergence
- ignition transient, thrust termination

(J. Levine)

S. Meeting Comments. The procedure for papers worked well this year, and the premeeting material contained most of the papers. During the meeting, there should be less in the way of presentation and more in the way of discussion. The 1981 subcommittee meeting tentatively will be arranged for by Chemical Systems Division, Sunnyvale, CA, (R. Hermsen) in February 1981. (D. George)

ACTION ITEMS	PERSONNEL*
1. Write the procedure for handling the analysis of expended inerts.	J. Lamberty
2. Chair a workshop on spin effects of space motors (winter 1981).	W. Brundige
3. Distribute write-up on Standard Method for Burn Rate Determination.	D. George
4. Establish a consistent data bank of thermochemical data and heats of formation, and provide a mechanism for its distribution.	D. George, C. Selph
5. Static Test Panel--to examine what performance parameters are currently being measured versus what parameters should be measured. Where, how, and how many measurements are appropriate? How should the data be handled in its reduction and interpretation?	C. Beckman, M. Ditore, E. Landsbaum
6. Write a procedure for handling slag analysis in rocket motors.	J. Lamberty, W. Brundige
7. Provide write-up on reporting and format of performance data from motor test firings.	J. Lamberty, W. Brooks

---

* First name on list should initiate action and coordinate with others listed to resolve the action items.

Appendix 1: Attendees

13th PERFORMANCE STANDARDIZATION SUBCOMMITTEE MEETING

Abbett, M.	Acurex-Aerotherm/Mountain View
Beckman, C.	AFRPL/Edwards AFB
Brooks, W. T.	Hercules/McGregor
Brundige, W. N.	Thiokol/Elkton
Chan, G. O.	Aerojet Strategic/Sacramento
Chang, I-Shih	Aerospace/El Segundo
Cherry, S.	KVB/Tustin
Chiba, Z.	Acurex/Mountain View
Coats, D.	SEA/Santa Ana
Daines, W.	Hercules/Magna
Ditore, M. J.	ASPC/Sacramento
Escallier, P. M.	NWC/China Lake
Geniec, W.	Rocketdyne/Canoga Park
George, S.	AFRPL/Edwards AFB
Green, R. L.	Boeing/Seattle
Harry, D. P.	TRW/Redondo Beach
Hege, H. F.	CPIA/Laurel
Hermsen, R. W.	UT-CSD/Sunnyvale
Hoffman, J.	Purdue Univ./W. Lafayette
Hunter, K.	KVB/Tustin
Kirshner, T. J.	Thiokol/Elkton
Lamberty, J. T.	UT-CSD/Sunnyvale
Landsbaum, E. M.	Aerospace/Los Angles
Lasley, G.	Thiokol/Brigham City
Levine, J. N.	AFRPL/Edwards AFB
Little, R. R., Jr.	ARO/Arnold AFS
Lyon, J. M.	NOS/Indian Head
Mikkelsen, C. D.	Thiokol/Huntsville
Mockenhaupt, J. D.	Aerojet Strategic/Sacramento
Nickerson, G. R.	SEA/Santa Ana
Procinsky, I. M.	ARC/Gainesville
Radke, R.	MICOM/Redstone
Runyan, R. B.	ARO/Arnold AFS
Salita, M.	Thiokol/Brigham City
Seibert, J. R.	Aerojet Tactical/Sacramento
Walsh, T. J.	TRW/San Bernardino

Appendix 2: Meeting Agenda

AGENDA

PERFORMANCE STANDARDIZATION SUBCOMMITTEE
FEBRUARY 14-15, 1980

RED LION INN
2001 Point West Way
SACRAMENTO, CALIFORNIA

Thursday, February 14 — Del Paso Room

08:30 A.M.	Opening Remarks D. George, PSS Chairman AFRPL, Edwards, CA
08:45 A.M.	Improved Solid Performance Program (SPP) G. Nickerson, D. Coats--Software and Engineering Associates, Santa Ana, CA R. Hermsen, J. Lamberty--Chemical Systems Division, Sunnyvale, CA
10:00 A.M.	BREAK
10:30 A.M.	One-Dimensional, Three-Phase Flow Reacting Gas with Mass Transfer S. Hunter--KVB Engineering, Tustin, CA
11:00 A.M.	Particle Impact Erosion Z. Chiba--Acurex, Mountain View, CA
11:30 A.M.	Performance Methodology Status Summary J. Hoffman--Purdue University, W. Lafayette, IN
12:00 Noon	LUNCH
01:30 P.M.	Space Motor Combustion Spin Effects W. Brundige--Thiokol/Elkton, Elkton, MD
02:00 P.M.	Expended Inerts/Slag Performance Procedure J. Lamberty--Chemical Systems Inc., Sunnyvale, CA
02:30 P.M.	BREAK
03:00 P.M.	Burning Anomaly Rate Factor T. Kirschner--Thiokol/Elkton, Elkton, MD
03:30 P.M.	Particle Impingement Modelling/Performance Effects W. Daines--Hercules Inc., Magna, UT
04:00 P.M.	Nozzleless Motor Performance Mechanisms M. Procinsky--Atlantic Research Corp., Alexandria, VA

Friday, February 15 | Del Paso Room

08:30 A.M.	Annual Report and General Business D. George, PSS Chairman AFRPL, Edwards, CA
09:00 A.M.	Thermochemical and Heats of Formation Data J. Rendleman--AFRPL, Edwards, CA
09:30 A.M.	Efficiency Definitions D. Coats--Software and Engineering Assoc., Santa Ana, CA
10:00 A.M.	BREAK
10:30 A.M.	Boundary Layer Study M. Salita--Thiokol/Wasatch, Brigham City, UT
11:00 A.M.	Vertical Force Test Measurement for MX Performance Measurements and Data Reduction E. Turner, R. Little--ARO, Arnold AFS, TN
12:00 Noon	LUNCH
01:30 P.M.	Three-Dimensional Time-Dependent Analysis J. Hoffman--Purdue University, W. Lafayette, IN
02:00 P.M.	Advanced Performance Methodology J. Levine--AFRPL, Edwards, CA
03:00 P.M.	BREAK
03:30 P.M.	Open Forum, Items of Opportunity, Future Plans

MEETING CHAIRMAN AND ARRANGEMENTS COORDINATOR:

M. Ditore
Aerojet Solid Propulsion Co.
Sacramento, CA

MEETING COORDINATOR:

H. F. Hege
Chemical Propulsion Information Agency
Laurel, MD

Appendix 3: Performance Standardization Meeting Objectives

OBJECTIVE

DEVELOP AND ESTABLISH A STANDARD METHODOLOGY TO PREDICT DELIVERED PERFORMANCE OF SOLID ROCKET MOTORS

QUESTIONS

- ARE THE PROPER ISSUES BEING ADDRESSED?
- ARE THE RIGHT PERSONNEL SPECIALISTS PARTICIPATING ON THE PSS?
- WHAT SHOULD THE METHODOLOGY CONSIST OF?
- WHAT ARE THE FUTURE PERFORMANCE PREDICTION CAPABILITY NEEDS?

IMPROVED SPP INTERIM VERSION NOW AVAILABLE FOR DISTRIBUTION

- SUBMIT REQUEST, SEND TAPE TO RPL

- WILL RECEIVE PROGRAM, THERMO TAPE, SAMPLE CASE INPUT, OUTPUT, DRAFT MANUAL

- APPLY PROGRAM, GIVE FEEDBACK

JANNAF EXECUTIVE COMMITTEE

- PSS CONCLUDE LIQUID ROCKET PERFORMANCE ACTIVITIES
- INTERACTION AMONG SUBCOMMITTEES
- DEFINE TASKS, PLAN APPROACH, ESTABLISH COMPLETION DATE
- PUBLICATIONS

THERMOCHEMICAL DATA

(STANDARD SET)

- SEND THERMO TAPE TO RPL FOR COMPARISON
- DISTRIBUTE THERMO DATA TAPE WITH SPP
- OBTAIN "LATEST" DIRECT FROM McBRIDE AND USE OR UPDATE OWN
- ESTABLISH INITIAL SET, PERIODIC UPDATE, VERIFICATION PROCEDURE

HEATS OF FORMATION

(STANDARD SET AND VALUES)

INGREDIENT CATEGORIES

- BINDER
- FUEL
- OXIDIZER
- PLASTICIZER
- CURATIVE
- OXIDANT
- ADDITIVES

- SELECT LIST OF COMMON INGREDIENTS
- PROVIDE DENSITY, MOLECULAR WEIGHT, H_F, FORMULA
- REVIEW, EVALUATE AND SELECT STANDARD VALUES

PERFORMANCE MEASUREMENTS

MOTOR

- WHAT PARAMETERS SHOULD BE MEASURED? (PRE AND POST TEST)
- WHERE (LOCATION) SHOULD THE MEASUREMENTS BE TAKEN?
- HOW AND HOW MANY OF EACH TYPE OF MEASUREMENT SHOULD BE TAKEN?
- HOW SHOULD THE DATA BE PROCESSED AND HANDLED?
- HOW SHOULD THE DATA BE REDUCED AND INTERPRETED?

PERFORMANCE MEASUREMENTS

PHENOMENA

- DATA TO CHARACTERIZE MECHANISM BEHAVIOR
- WHAT EXPERIMENTS SHOULD BE CONDUCTED?
  - APPARATUS
  - INSTRUMENTATION
  - TEST CONDITIONS

PERFORMANCE STANDARDIZATION SUBCOMMITTEE

13TH MEETING

SACRAMENTO, CA

14-15 FEBRUARY 1980

VIEW GRAPHS

IMPROVED SOLID PERFORMANCE PROGRAM (SPP)

G.R. NICKERSON
SOFTWARE AND ENGINEERING ASSOCIATES, INC.
354 BROOKHOLLOW DRIVE
SANTA ANA, CA 92705
(714) 751-3242

SPP

IMPROVED SOLID PERFORMANCE PROGRAM

OBJECTIVE:	TO DEVELOP AND DEMONSTRATE A COMPUTER PROGRAM WHICH WILL PREDICT SOLID ROCKET MOTOR DELIVERED SPECIFIC IMPULSE WITHIN ± 0.5% AND THRUST AND TOTAL IMPULSE WITHIN ± 3%
PHASE I:	TWO-DIMENSIONAL TWO-PHASE FLOW (TD2P)
PHASE II:	IMPROVED TECHNICAL ELEMENTS
BOTH I & II:	WORKSHOPS COMPUTER PROGRAM REQUIREMENTS PROGRAM VERIFICATION & VALIDATION DOCUMENTATION

Software and Engineering Associates, Inc.
354 Brookhollow Drive
Santa Ana, CA 92705

(714) 751-3242

SEA

SPP INTERIM VERSION

MAJOR ACHIEVEMENTS

1. DEVELOPMENT OF THE FULLY COUPLED TRANSONIC (FCT)
2. DEVELOPMENT OF A PARTICLE SIZE MODEL FOR ALUMINA
3. IMPROVEMENTS IN RELIABILITY AND APPLICABILITY
4. DOCUMENTATION

SPP INTERIM VERSION

NEW FEATURES

PROGRAM INPUT

- SIMPLIFIED PROCEDURES
- UPDATED AND EXPANDED THERMOCHEMICAL DATA
- REACTANTS LIBRARY

TECHNICAL ELEMENTS

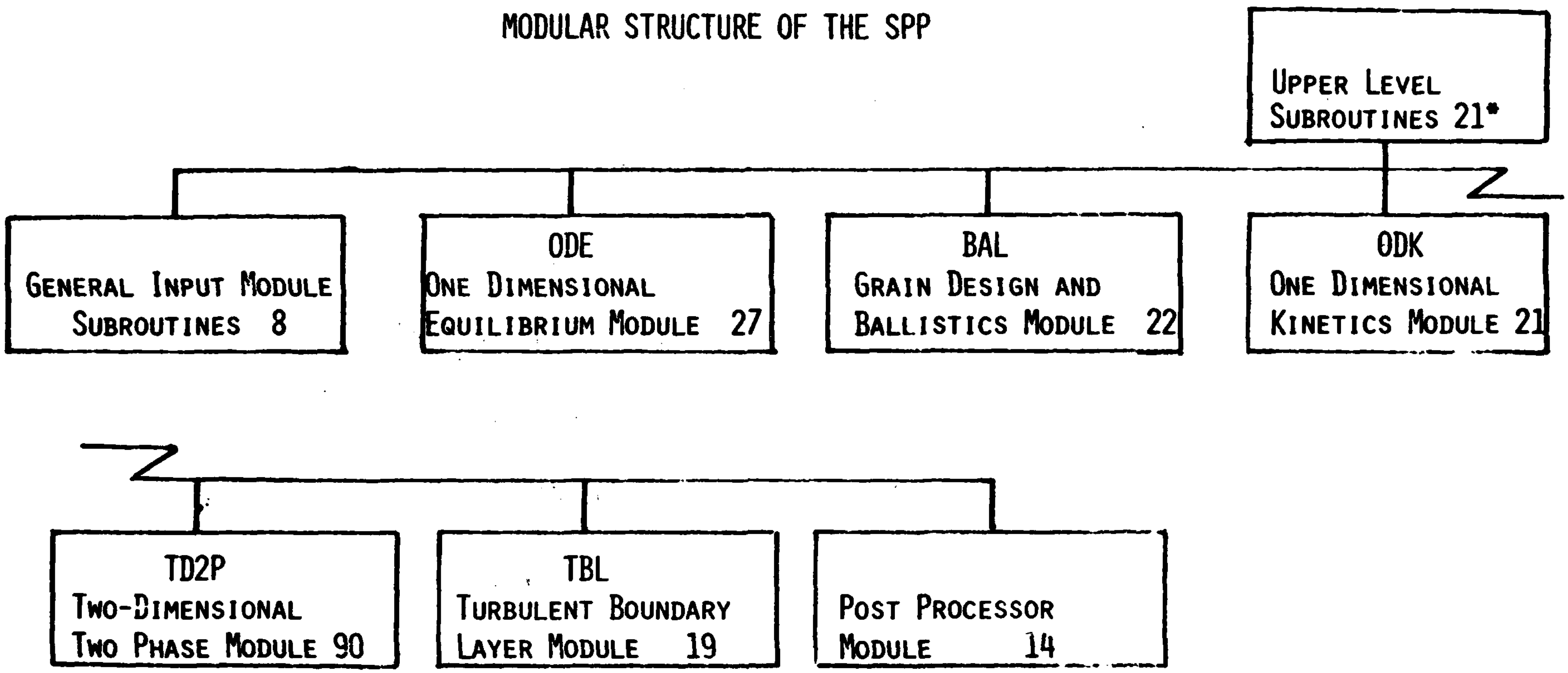
- NOZZLE INLET GEOMETRY (TD2P/ATS)
- PARTICLE IMPINGEMENT (TD2P)
- ACCURACY STUDY
- IMPROVED NUMERICAL TECHNIQUES
- PARTICLE SIZE CORRELATION
- PARTICLE DRAG LAW
- COMBUSTION EFFICIENCY MODEL
- THROAT EROSION MODEL

PROGRAM OUTPUT

- SIMPLIFIED PROCEDURES
- SUMMARY PAGES
- PLOTTING CAPABILITY

SEA

MODULAR STRUCTURE OF THE SPP



*NUMBER OF SUBROUTINES IN MODULE. NUMBER OF SUBROUTINES IN SPP = 222.

SEA

COMPUTER PLOTTING

MODULE	PLOTS
SPP	$I_{SP_{TH}}$ VS AREA RATIO EFFICIENCIES VS AREA RATIO I_{SP_D} VS AREA RATIO PRESSURE VS TIME THRUST VS TIME
TD2P / FCT,MOC	FCT GRID MOC NET MACH NO. PROFILES GAS STREAMLINES PARTICLE STREAMLINES DENSITY CROSSECTIONS WALL PRESSURE & TEMPERATURE
GDB	WEBB BURNBACK VS TIME (AXIAL AND TRANSVERSE)

Figure 1: Case 3, Characteristic Net, γ=1.2, Source Flow, NILP=10

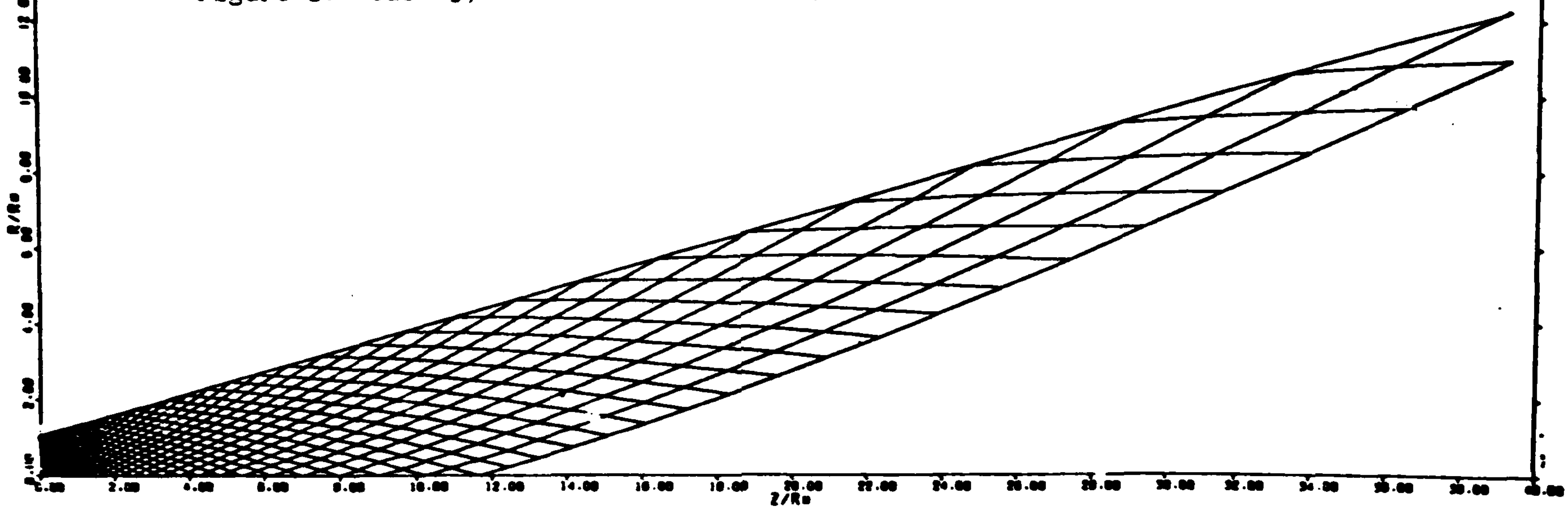
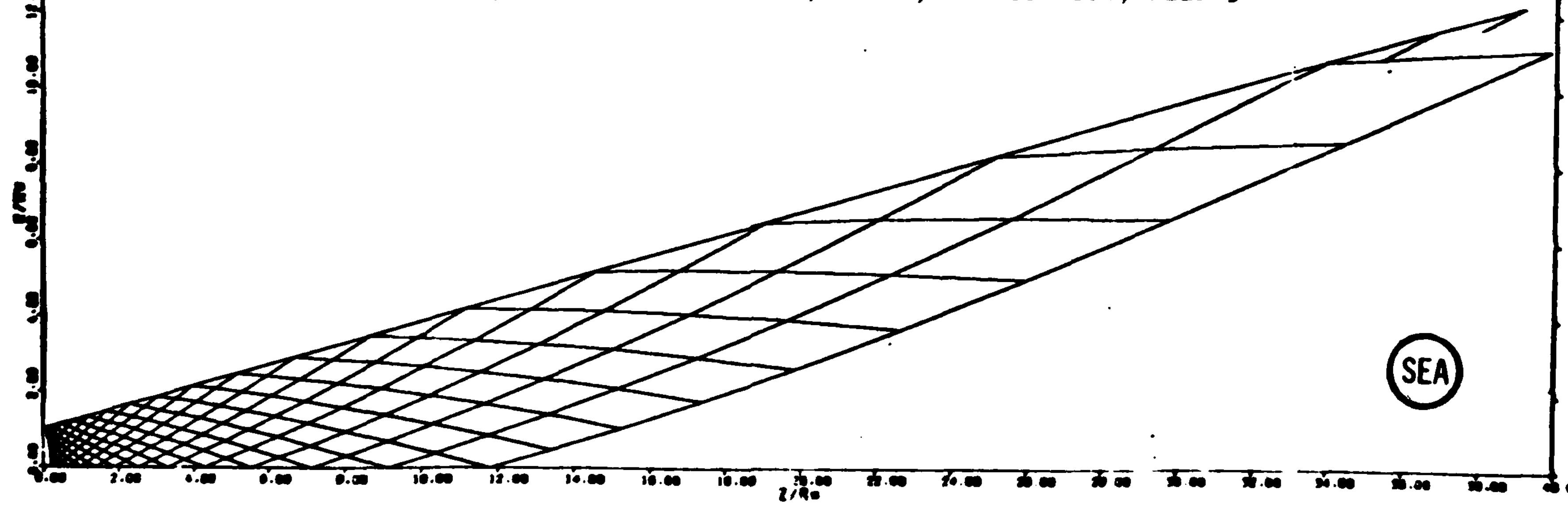


Figure 2: Case 4, Characteristic Net, γ=1.2, Source Flow, NILP=5



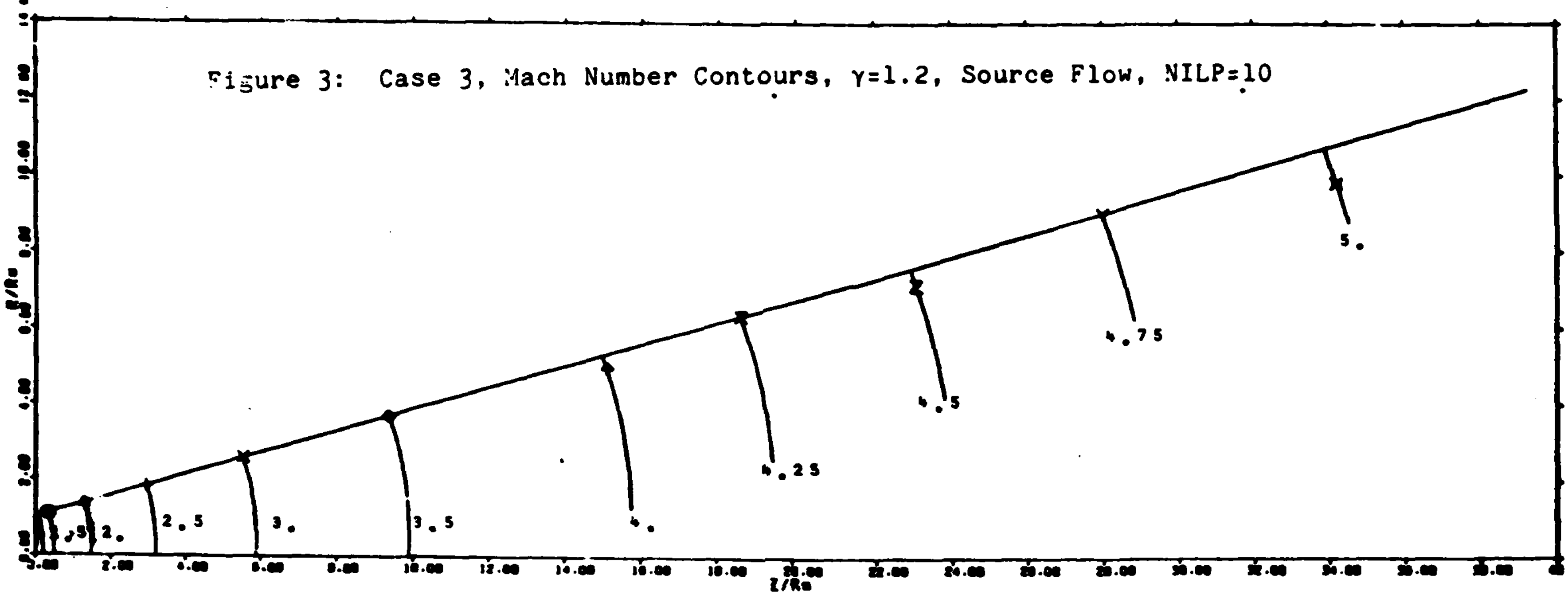


Figure 3: Case 3, Mach Number Contours, γ=1.2, Source Flow, NILP=10

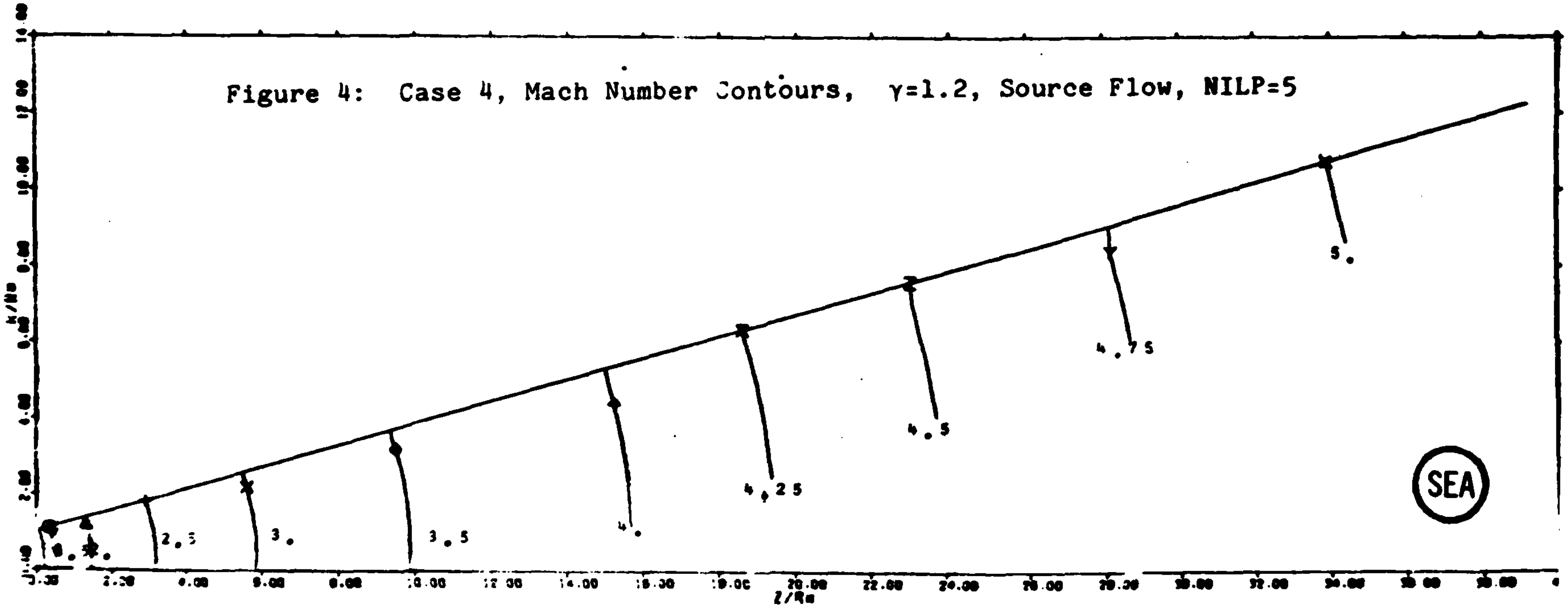


Figure 4: Case 4, Mach Number Contours, γ=1.2, Source Flow, NILP=5

Figure 18: Case 14 CHARACTERISTIC NET D_p=3.4, 6.4, 11.9, IUS Large Motor

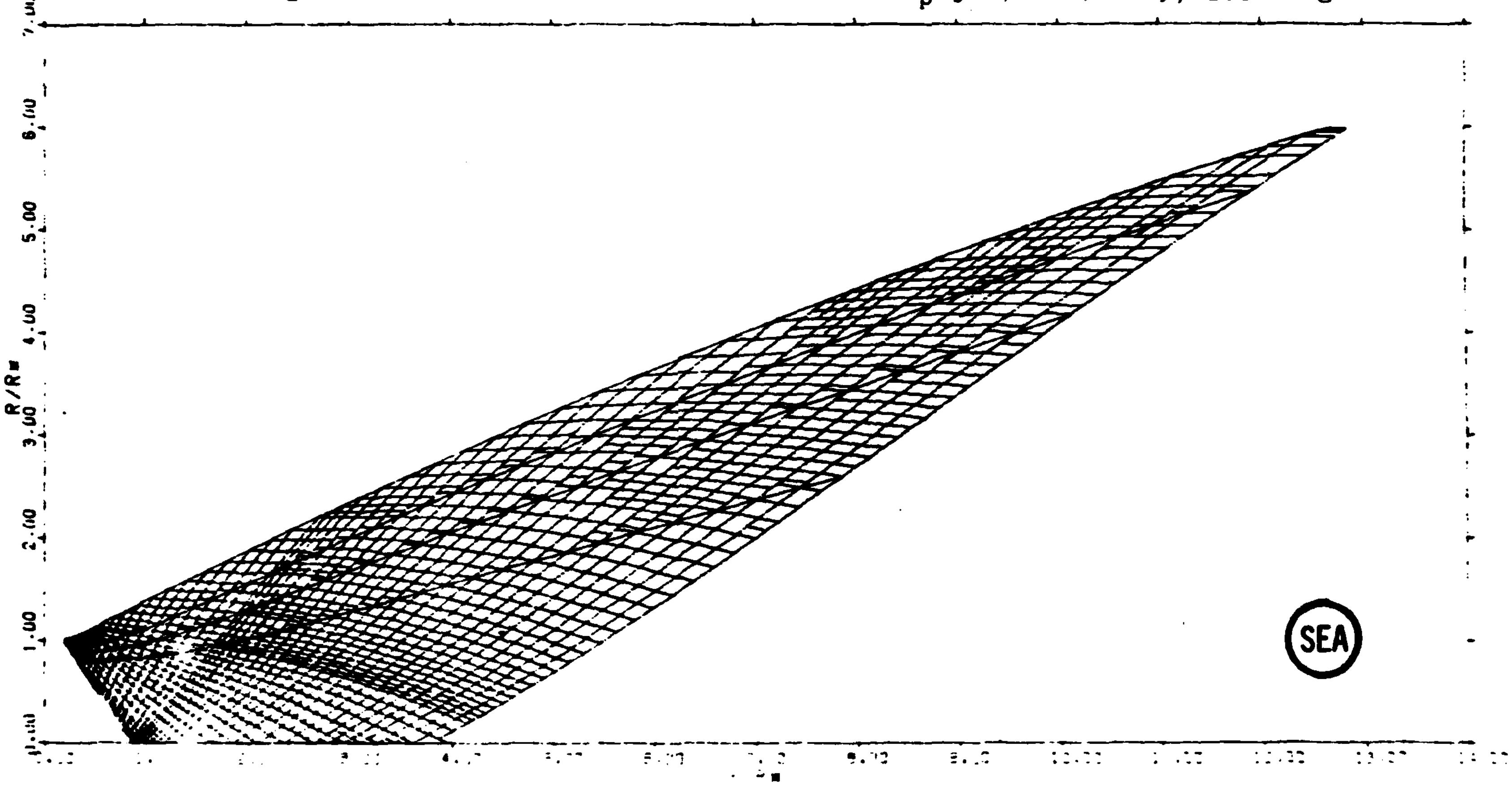
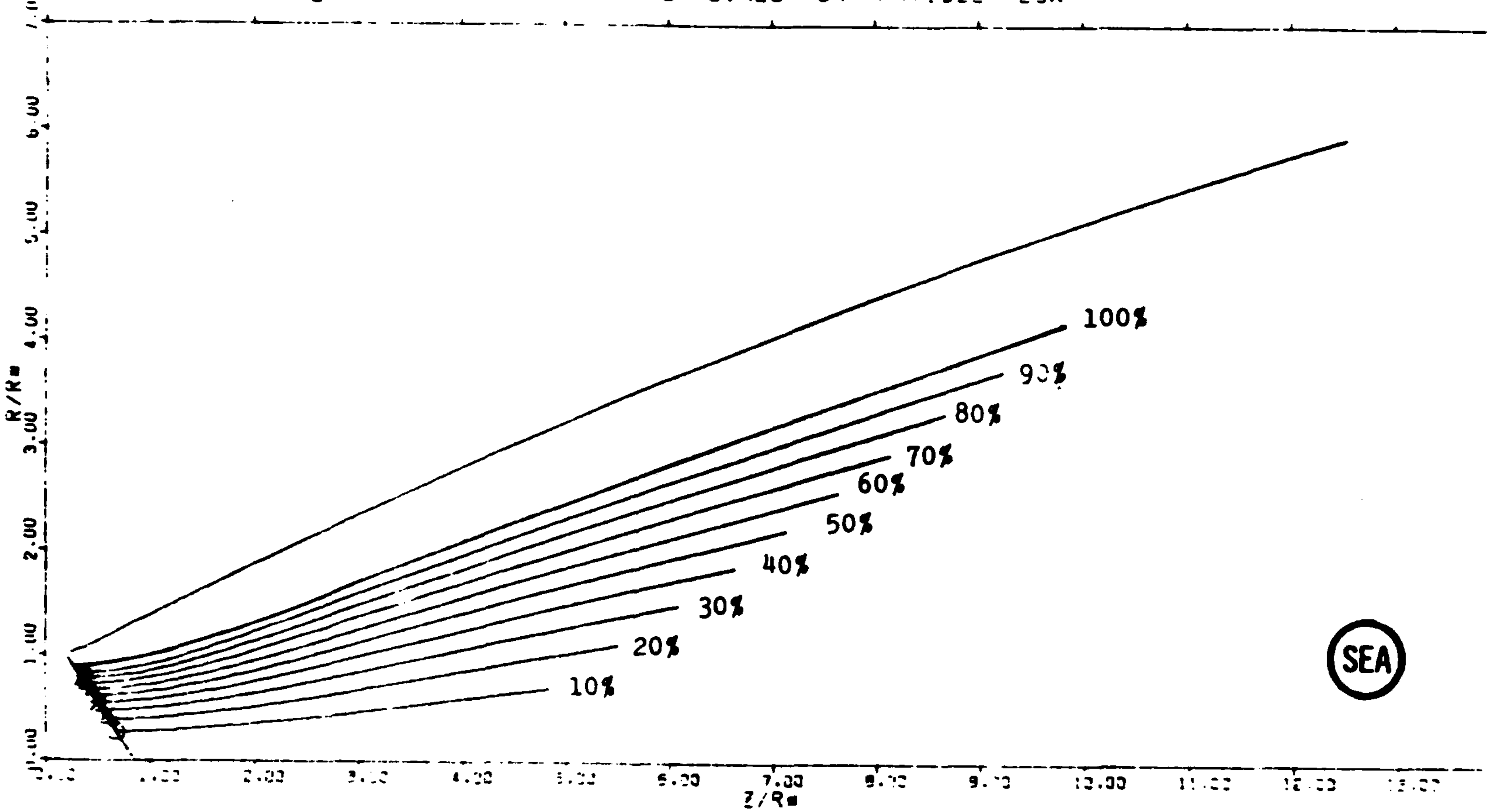
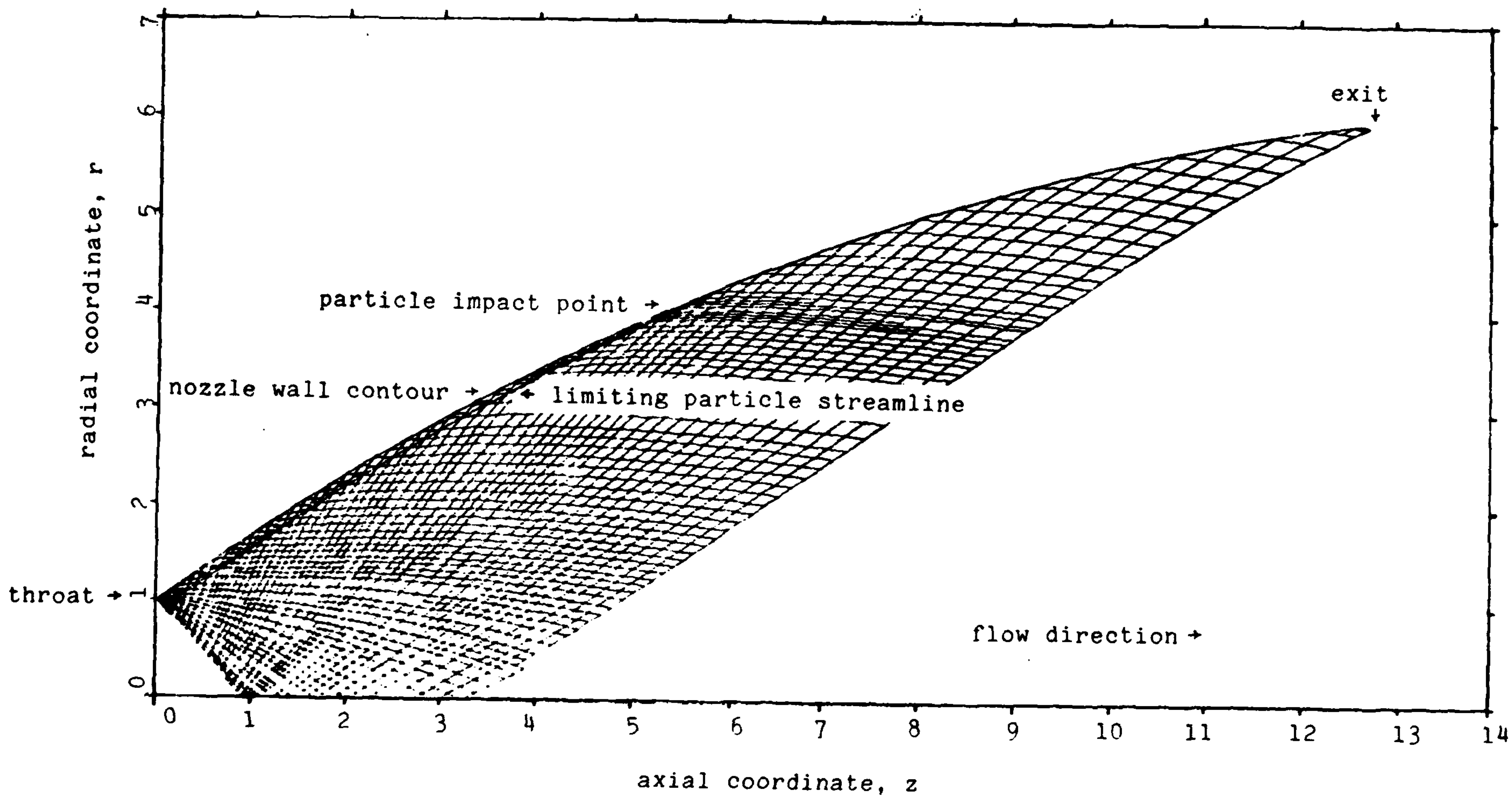


Figure 15: Case 12 STREAMLINES FOR PARTICLE FLOW NILP=40, IUS Large Motor



SPP/TD2P PARTICLE IMPINGEMENT
WITH NOZZLE WALL

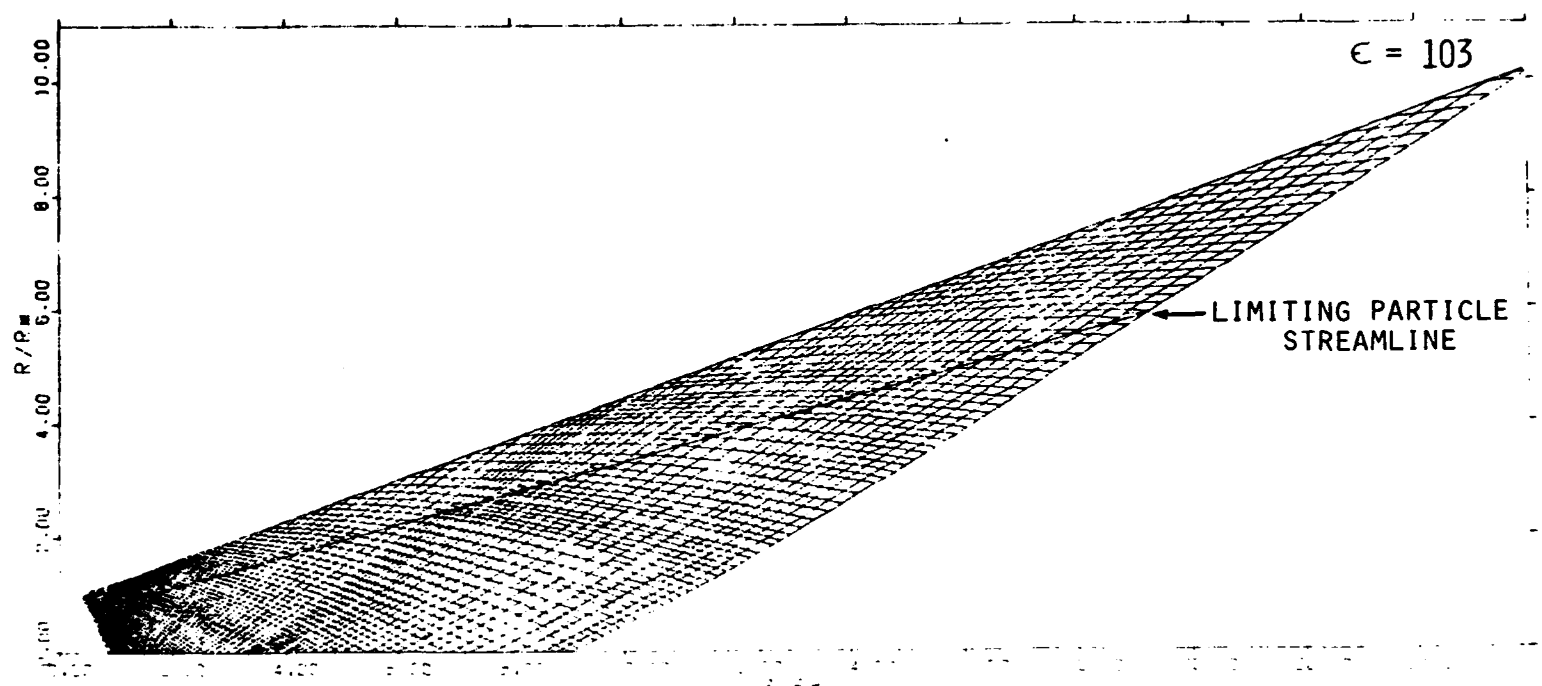


AIM MOTOR

METHOD OF CHARACTERISTICS SOLUTION

FROM APPROXIMATE TRANSONIC ANALYSIS

CHARACTERISTIC NET

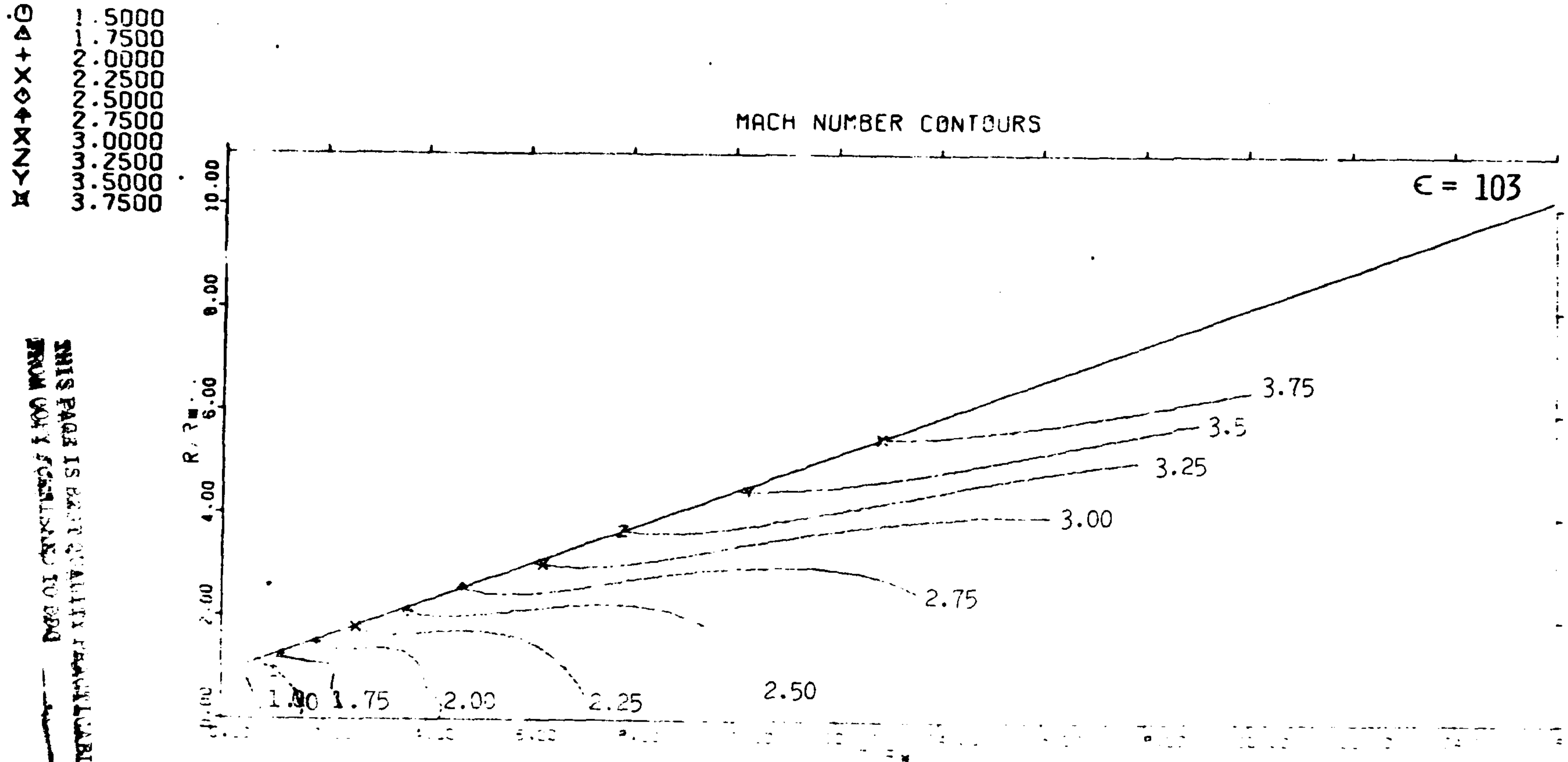


SEA

AIM MOTOR

METHOD OF CHARACTERISTICS SOLUTION

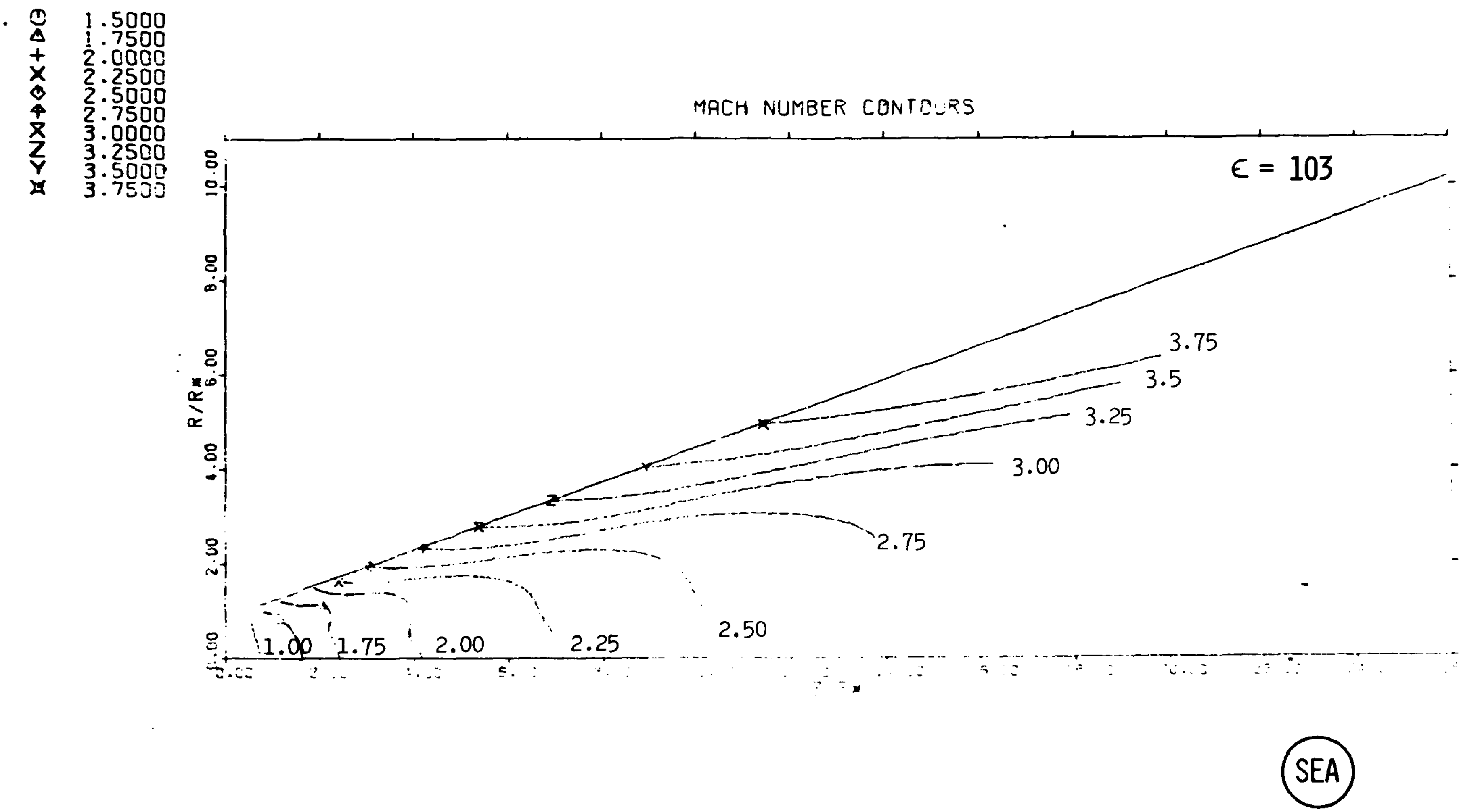
FROM APPROXIMATE TRANSONIC ANALYSIS



AIM MOTOR

METHOD OF CHARACTERISTICS SOLUTION

FROM FULLY COUPLED TRANSONIC



SIX MOTOR TEST CASES

USED FOR PROGRAM CHECK OUT, VERIFICATION, AND DEMONSTRATION

	Motor	Propellant Type	Grain Geometry	$\bar{P}_C$	D_T	Submergence %	R_C/R_T Up/Dn	Expansion Section	ϵ
[illegible]	Extended Delta	CTPB 86% solids 16% Al	8 point star	560	4.28	25.0	1/1	Contour	30.8
[illegible]	Titan IIIC Stage 0	PBAN 86% solids 16% Al	Segmented cylinder	550	37.5	0	.39/.39	Cone	8.0
[illegible]	[illegible]	[illegible]/HMX 90% solids 18% Al	Conocyl	900	4.04	10.0	2/3.9	Contour	50.3
4	IUS Large Motor	HTPB 86% solids 18% Al	Cylinder	550	6.85	35.0	2/1	Contour	35.7
[illegible]	A[illegible]	PBAN 84.5% solids 16.4% Al	Conocyl	730	2.03	8.5	2/2	Cone	103.2
[illegible]	Reduced Smoke [illegible]	HTPB 87% solids 0% Al	Modified cylinder	1520/370	1.2	0	1.5/1.5	Cone	2.0
7.	MM[illegible] St[illegible] 2 Wing VI	CTPB 86% solids 15% Al	Modified cylinder	445	9.63	13.4	.93/2.0	Contour	24.8

EFFICIENCY PREDICTIONS FOR 6 MOTOR TEST CASES

MOTOR	BL	EROSION MEAS.	KIN	SUB	TD2P ATA,(FCT)	LOSS	MEAS.	% DIFF.
1. EXTENDED DELTA	.9947	.9962	.9943	.9921	.9395 (.9394)	.9184 (.9184)	.9207	-.25 (-.25)
2. TITAN IIIC STAGE 0	.9978	.9977	.9994	1.0	.9637 (.9621)	.9587 (.9571)	.9548	+.41 (+.24)
3. C4 STAGE 3 (ADP)	.9945	.9952	.9949	.9934	.9418 .9384	.9213 (.9183)	.9192	+.23 (-.09)
4. IUS LARGE MOTOR	.9954	.9944	.9942	.9930	.9359 (.9365)	.9157 (.9153)	.9183	-.28 (-.32)
5. AIM	.9930	.9971	.9921	.9936	.9243 (.9219)	.9021 (.8998)	.9030	-.10 (-.36)
6. REDUCED SMOKE MAVERICK	.9964	.9904	.9988	1.0	.9938 (.9932)	.9795 (.9789)	.9793	(+.02) (-.04)
7. MMII STAGE 2 WING 6	.9953	.9993	.9941	.9948	.9492 (.9406)	.9336 (.9251)	.9271	+.70 (-.22)

SPP REMAINING WORK TASKS

SEA

Phase II Improved Technical Elements

Review of Modules:
GD&B
ODK
TD2P
TBL

V & V Phase II

Sensitivity Analysis
Appl. and Accuracy
Plot Demo
10 Motor Test Cases
Test Case Delivery

Phase II Documentation

Final Report, Vol. I, II, & III

SPP Delivery

SPP REMAINING WORK TASKS

TASK	AS OF 1/80 % COMPLETE
10 MOTOR VALIDATION TEST CASES	25%
GRAIN DESIGN & BALLISTICS	80%
IMPROVED CHAMBER FLOW CHARACTERIZATION	90%
IMPROVED EROSIVE BURNING	90%
WALL TEMPERATURE MODEL	0%
FINAL REPORT	20%

Appendix 5: Improved SPP - Fully Coupled Transonic Module Status Report

PERFORMANCE STANDARDIZATION SUBCOMMITTEE

13TH MEETING

SACRAMENTO, CA

14-15 FEBRUARY 1980

IMPROVED SOLID PERFORMANCE PROGRAM (SPP)

FULLY COUPLED TRANSONIC MODULE

STATUS REPORT

D.E. COATS

SOFTWARE AND ENGINEERING ASSOCIATES, INC.
354 BROOKHOLLOW DRIVE
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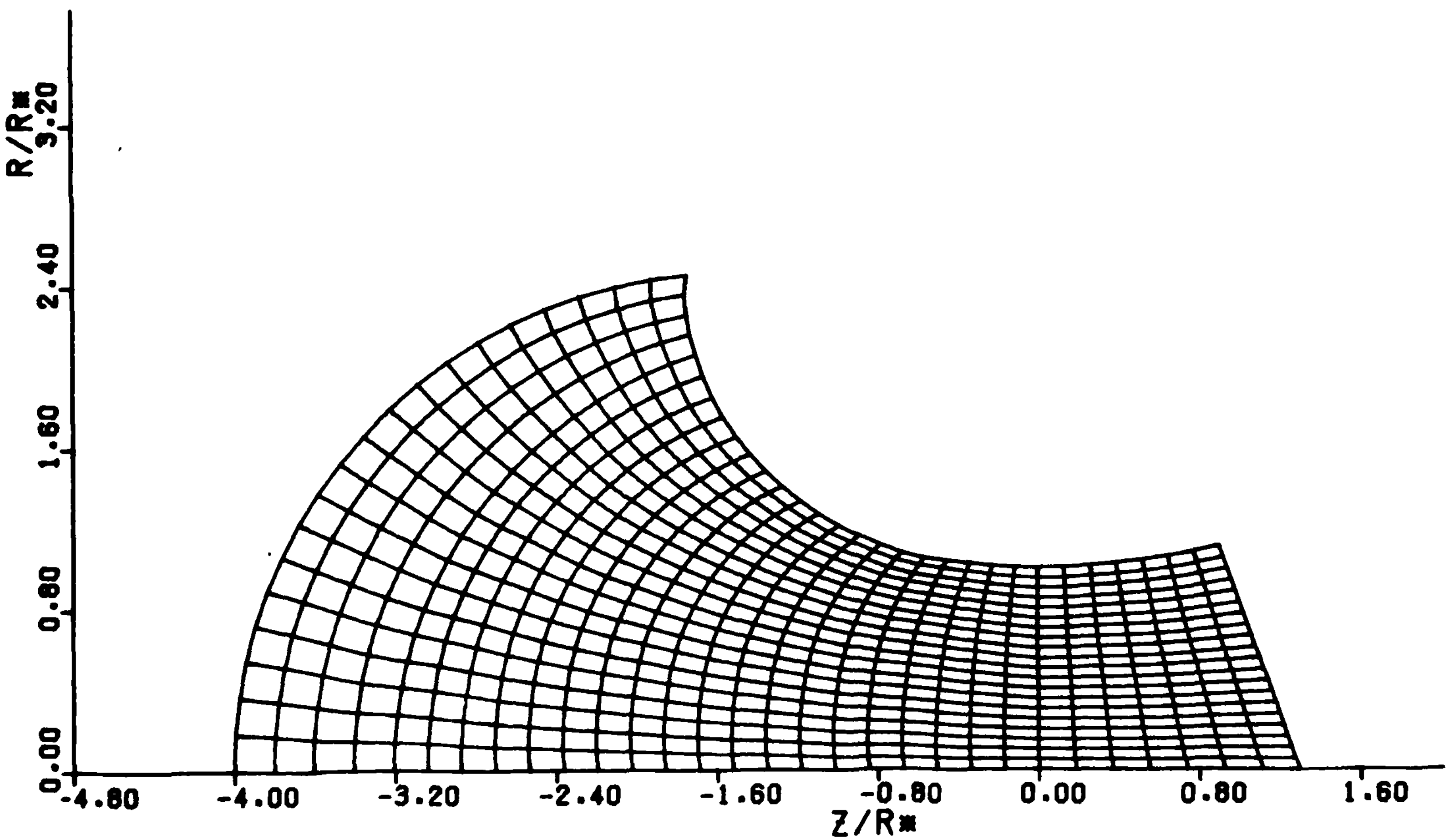
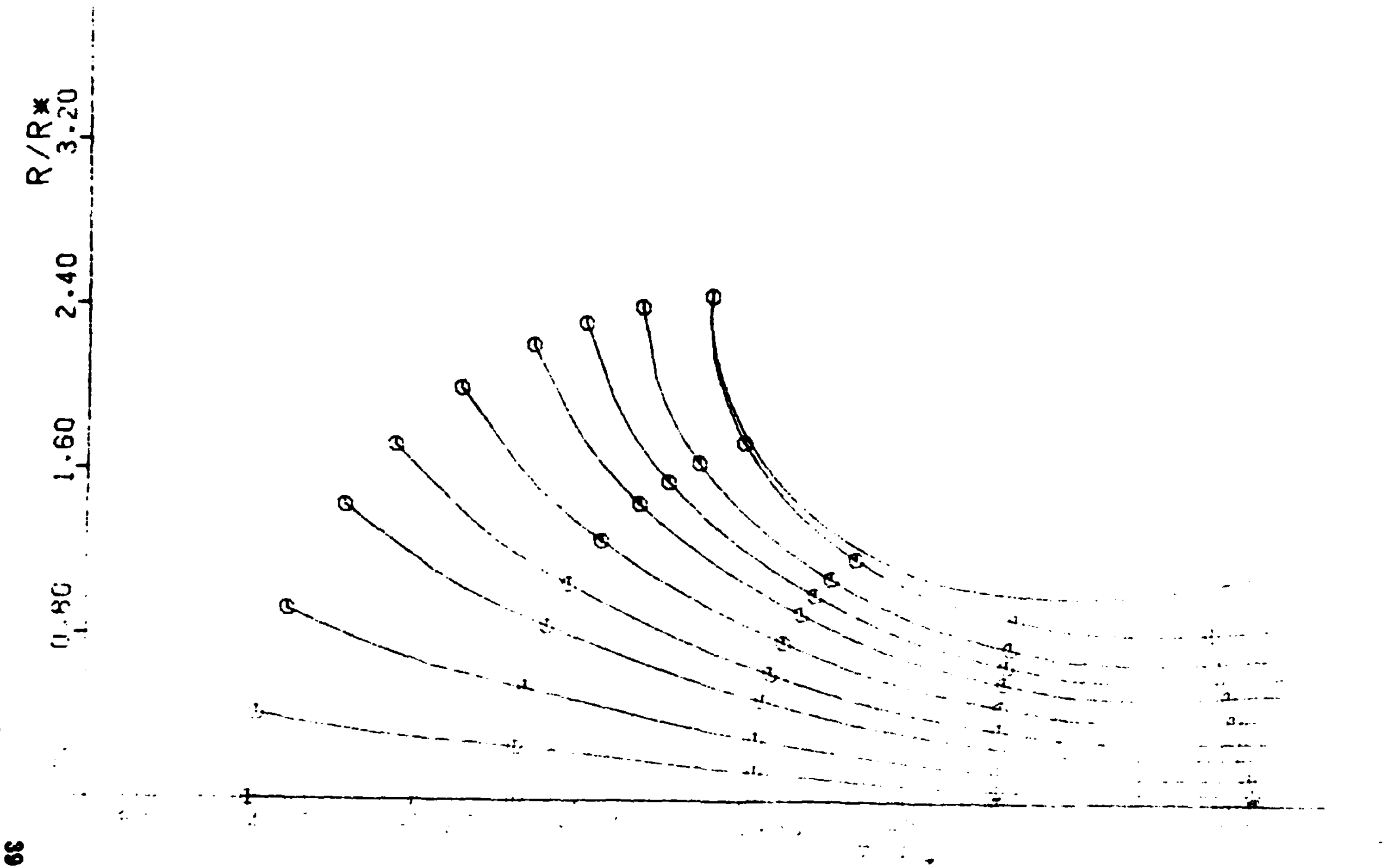
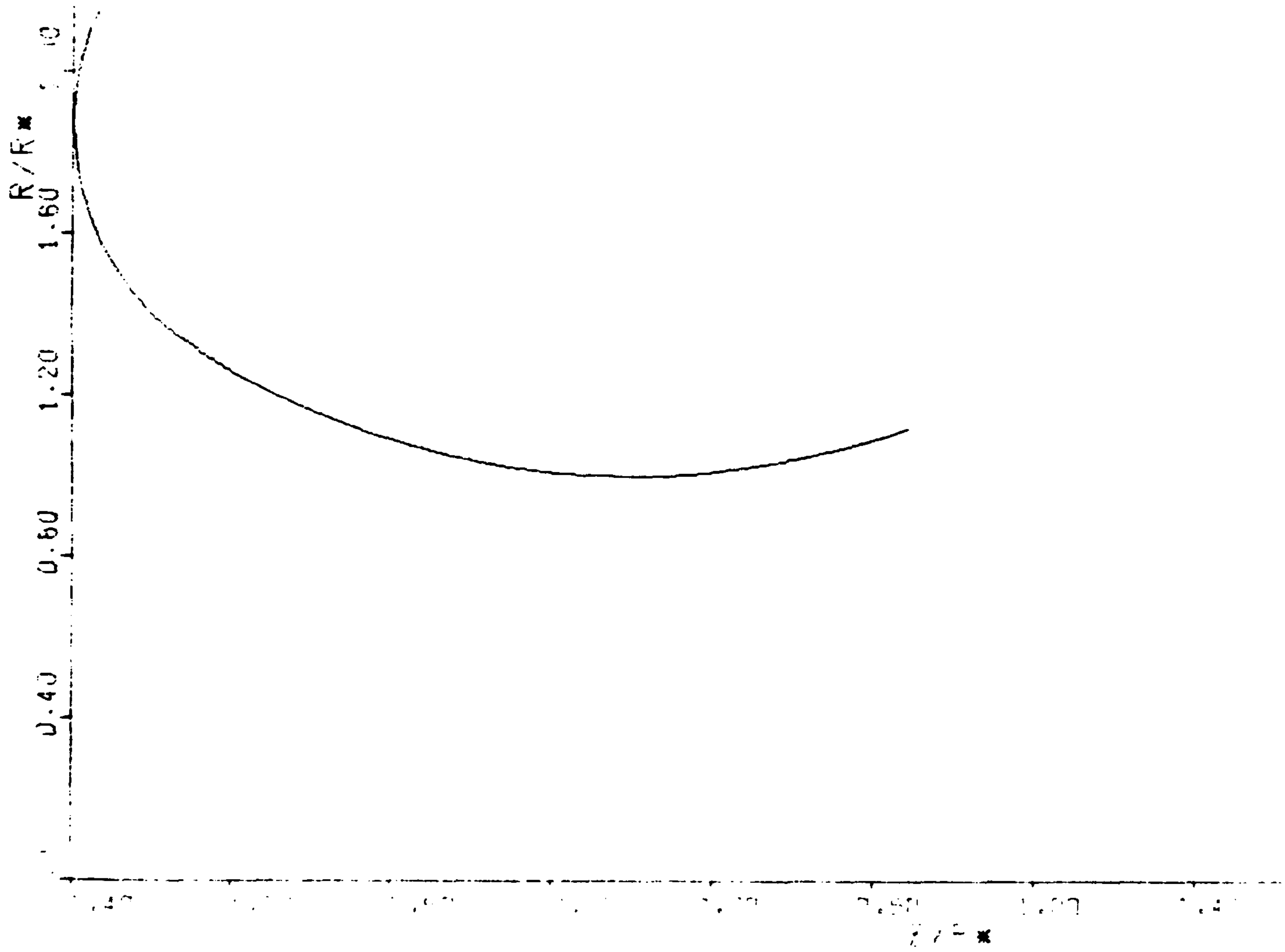
TYPICAL MESH - C4 STAGE 3 (ADP)



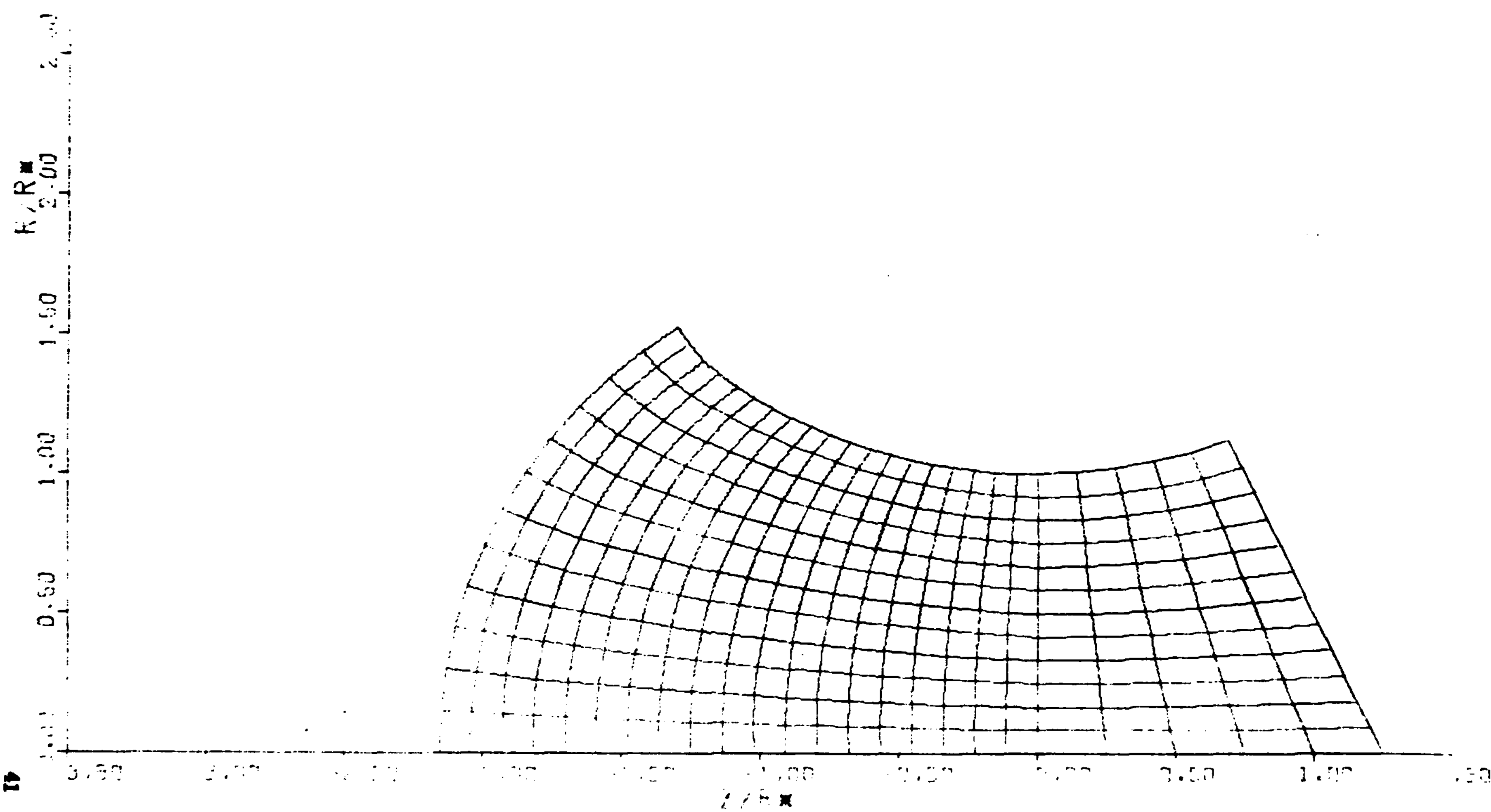
PARTICLE TRAJECTORIES



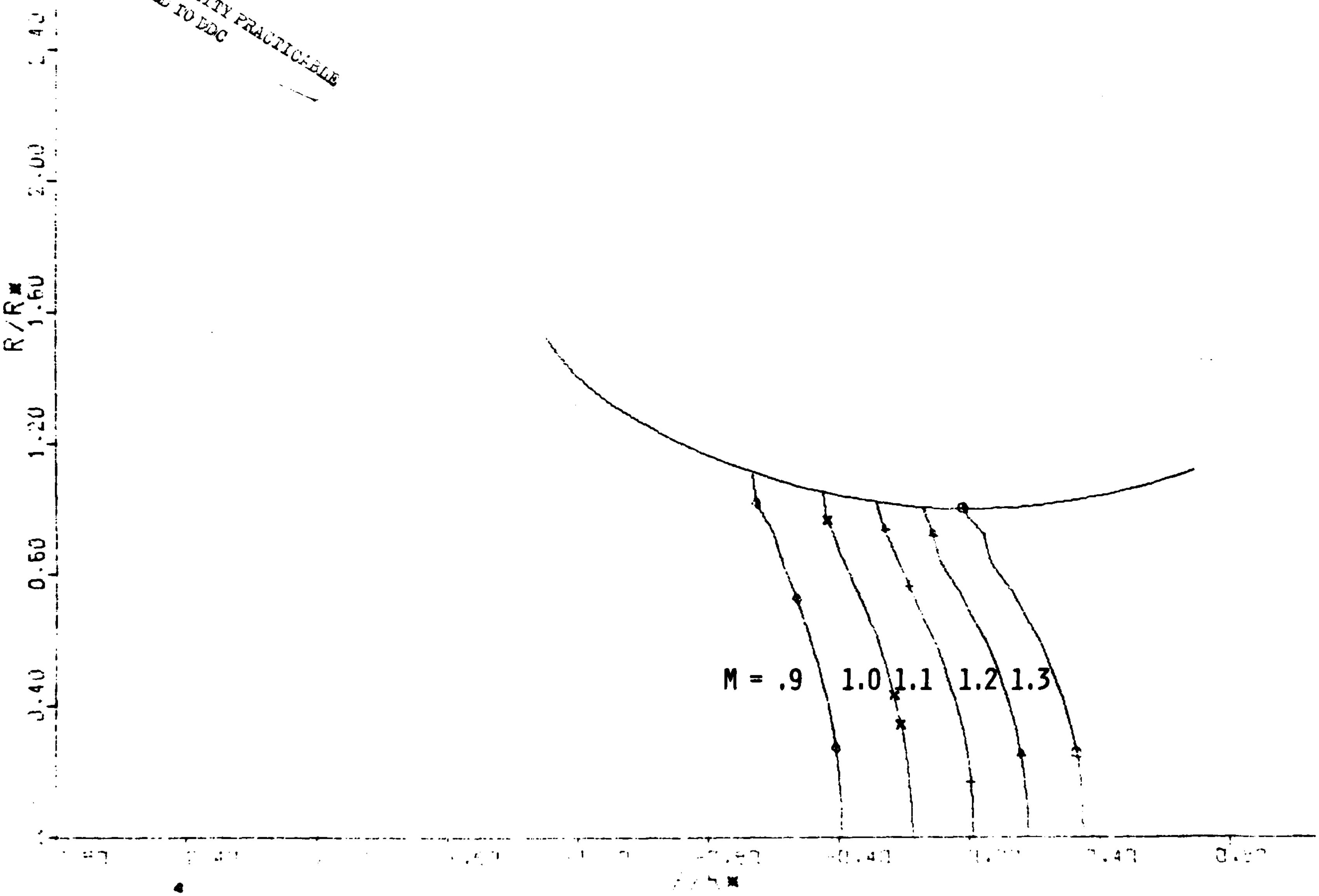
AIM INLET WALL



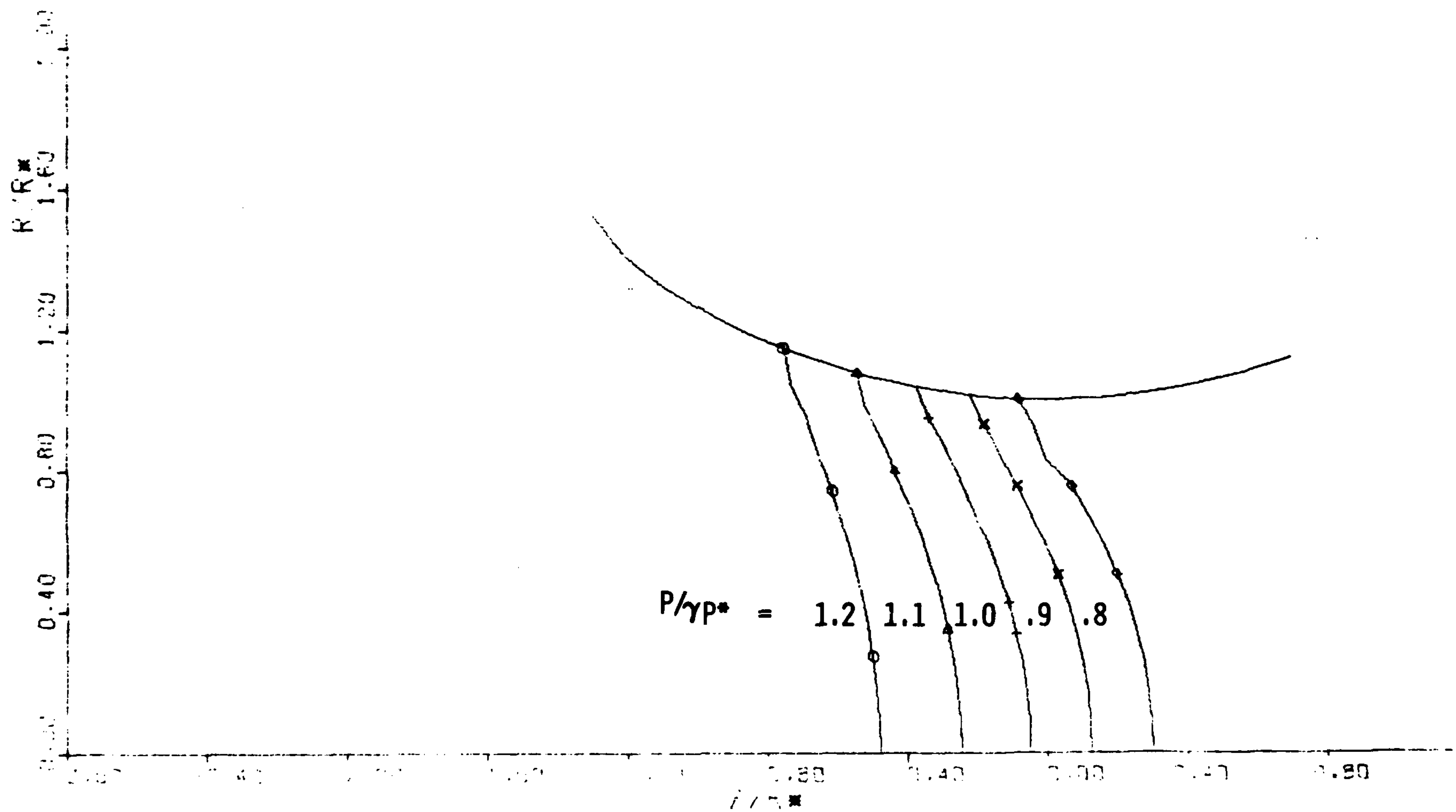
REGION 1 MESH FOR AIM MOTOR



CONSTANT MACH NUMBER CONTOURS FOR THE AIM MOTOR



CONSTANT PRESSURE CONTOURS FOR THE AIM MOTOR



SPP FULLY COUPLED TRANSONIC MODULE STATUS

REGION I CALCULATIONS WORK WELL AND ARE REASONABLY RELIABLE.

PROBLEMS STILL REMAIN WITH REGION II - SOLUTIONS ARE EXPENSIVE AND DIFFICULT TO OBTAIN.

RECOMMENDATION:
THAT THE APPROXIMATE TRANSONIC ANALYSIS BE USED FOR PARAMETRIC STUDIES AND THE FCT MODULE BE USED FOR FINAL PERFORMANCE PREDICTION.

PERFORMANCE STANDARDIZATION SUBCOMMITTEE

13TH MEETING

SACRAMENTO, CA

14-15 FEBRUARY 1980

IMPROVED SOLID PERFORMANCE PROGRAM (SPP)

KINETIC SCREENING STUDY

D.E. COATS

SOFTWARE AND ENGINEERING ASSOCIATES, INC.
354 BROOKHOLLOW DRIVE
SANTA ANA, CA 92705
(714) 751-3242

REACTION RATE SCREENING

MOTOR	RUN TIME (MIN) VS. REACTION SET		
	SCREENED SET	KVB SET +4	SPP 1975 SET
1 EXTENDED DELTA	9.8	15.9	23.7
2 TITAN IIIC STAGE 0	6.0	9.6	15.6
3 C4 STAGE 3 (ADP)	5.9	9.8	15.8
4 IUS LARGE MOTOR	5.2	9.1	15.3
5 AIM	6.7	10.7	19.7
6 REDUCED SMOKE MAVERICK	4.6	6.0	10.8
NO. OF REACTIONS	15	49	73
NO. OF SPECIES	21	21	26

REACTION RATE SCREENING

MOTOR	$\% \Delta I_{SP}$ VS SCREENED SET	
	KVB SET +4	SPP 1975 SET
1 EXTENDED DELTA	.01%	.05%
2 TITAN IIIC STAGE 0	.01%	.01%
3 C4 STAGE 3 (ADP)	.04%	.06%
4 IUS LARGE MOTOR	.01%	.05%
5 AIM	.02%	.08%
6 REDUCED SMOKE MAVERICK	.01%	.07%

SEA

```
REACTIONS
H+H=H2,                A=1.09E18,  N=1.,     B=0.0,     JENSEN/JONES(1978)     002
H+CL=HCL,              A=1.45E22,  N=2.,     B=0.0,     JENSEN/JONES(1978)     003
OH+H=H2O,              A=3.22E22,  N=2.,     B=0.0,     JENSEN/JONES(1978)     006
CO+O=CO2,              A=2.54E15,  N=0.0,    B=4.37,    JENSEN/JONES(1978)     014
ALCL+CL=ALCL2,         A=3.0E16,   N=0.5,    B=0.0,     ESTIMATE
ALCL2+CL=ALCL3,        A=3.0E16,   N=0.5,    B=0.0,     ESTIMATE
END TBR REAX
H2+OH=H2O+H,           A=1.14E9,   N=-1.3,   B=3.627,   JENSEN/JONES(1978)     019
CO+OH=CO2+H,           A=1.69E7,   N=-1.3,   B=-0.656,  JENSEN/JONES(1978)     020
HCL+OH=H2O+CL,         A=1.30E13,  N=0.0,    B=2.087,   JENSEN/JONES(1978)     022
AL+HCL=ALCL+H,         A=5.E11,    N=-0.5,   B=5.673,   ESTIMATE               030
ALO+HCL=ALOCL+H,       A=1.E11,    N=-0.5,   B=5.673,   ESTIMATE               033
ALCL+OH=ALOCL+H,       A=1.E11,    N=-0.5,   B=5.619,   ESTIMATE               034
ALOH+OH=H+ALO2H,       A=1.E11,    N=-0.5,   B=5.627,   ESTIMATE               066
CL2+H=HCL+CL,          A=8.43E13,  N=0.0,    B=1.152,   JENSON/JONES(1978)
ALCL2+H=ALCL+HCL,      A=1.0E11,   N=-0.5,   B=1.795,   ESTIMATE
LAST REAX
```

Proposed Screened Reaction Set

A PROPOSED REACTION SET FOR KINETIC CALCULATIONS IN SOLID PROPELLANT ROCKET NOZZLES

BY

MARK SALITA

Thiokol / WASATCH DIVISION
A DIVISION OF THIOKOL CORPORATION
P.O. Box 524, Brigham City, Utah 84302 801/863-3511

Thiokol / WASATCH DIVISION

- GOAL - TO ELIMINATE THOSE KINETIC REACTIONS WHOSE EFFECT ON I_{SP} IS NEGLIGIBLE
- AFRPL/KVB HAS RECENTLY PROPOSED A SET OF 15 REACTIONS (USING THE BITTKER SCREENING CRITERION) THAT RESULTS IN LITTLE CHANGE IN I_{SP} FOR SIX MOTORS COMPARED TO A MORE COMPLETE SET OF 73 REACTIONS
- THIOKOL NOW PROPOSES TWO SUCCESSIVELY-SCREENED SETS OF 35 AND 16 REACTIONS (USING THE KUSHIDA SCREENING CRITERION)
- WHEN COMPARED TO THE MORE COMPLETE SET OF 73 REACTIONS FOR FOUR DIFFERENT TEST MOTORS, THE THIOKOL 16-SET YIELDS LESS I_{SP} CHANGE THAN THE AFRPL/KVB 15-SET AND AT 10% LESS CPU TIME
- THE EFFECTS OF PROPELLANT AND RATE DATA ON THESE RESULTS ARE BEING INVESTIGATED
- THE INTERMEDIATELY SCREENED SET OF 35 REACTIONS SHOULD BE USED FOR SOME MOTORS (E.G., HIGH EXPANSION RATIO)
- FURTHER DETAILS ARE PROVIDED IN THE FOLLOWING EXCERPT FROM THIOKOL MEMO NO. 2814-79-M132 (11/2/79)

Thiokol/WASATCH DIVISION

SALITA SCREENING PROCEDURE:

- IT HAS BEEN OBSERVED THAT THE EQUILIBRIUM PRODUCTS FOR MOST PROPELLANTS MAY BE SUB-DIVIDED INTO 3 GROUPS ACCORDING TO TYPICAL CONCENTRATIONS:

DOMINANT	SECONDARY	TERTIARY
H_2O	CO_2	Cl_2
CO	OH	NO
HCl	Cl	O_2
H_2	H	C
N_2	$AlCl$	N
Al_2O_3	$AlCl_2$	O
	$AlClO$	Al
	$AlCl_3$	

OTHER SPECIES USUALLY APPEAR IN NEGLIGIBLE CONCENTRATIONS.

- RETAINING ONLY THOSE REACTIONS OF THE 73 SPP-SET (1975) THAT CONTAIN THE
  1) FULL 21 SPECIES $\longrightarrow$ 35 REACTIONS
  2) DOMINANT/SECONDARY SPECIES ONLY $\longrightarrow$ 16 REACTIONS
- OF THE 16, 15 REACTIONS ARE THE ANALOGOUSLY-SCREENED SET STARTING WITH THE TRW SET (1967); 10 ARE SAME AS AFRPL/KVB.

C) Test Cases

The effect of reaction set upon I_{sp} was determined for four motors using the ODK module of the update-version of SPP with default step size and identical (1975) reaction rate data. The results are:

	MOTOR 1	MOTOR 2	MOTOR 3	MOTOR 4
A_e/A^*	15.08	53.21	109.20	246.17
I''_{sp} (restricted ODE)	296.57	316.14	331.59	342.75
$(I_{sp})_{ODK}$ (73 reacts)	296.40	313.98	329.00	339.57
$(I_{sp})_{ODK}$ (35 reacts)	296.38	314.02	---	339.40
$(I_{sp})_{ODK}$ (16 TC reacts)	296.25	313.86	328.63	339.10
$(I_{sp})_{ODK}$ (15 AFRPL reacts)	296.42	314.89	330.03	340.40
Error (Salita 35/73)	-0.02	+0.04	---	-0.17
Error (Salita 16/73)	-0.15	-0.12	-0.37	-0.47
Error (AFRPL 15/73)	+0.02	+0.91	+1.03	+0.83
SBU (73) (Computer Cost)	NA	590	696	1250
SBU (35)	234	311	---	768
SBU (16)	168	195	282	495
SBU (15)	188	228	312	563

IMPROVED TECHNICAL ELEMENTS FOR SPP

COMBUSTION EFFICIENCY MODEL NOZZLE THROAT EROSION MODEL	In interim version of SPP
AXIAL PRESSURE DROP EROSIVE BURNING	In new GDB module for 1980 version of SPP

APPROACH TO COMBUSTION EFFICIENCY PREDICTION

$$\bar{F} = \int_0^1 \int_0^1 F \, dm_D \, dm_e$$

$\bar{F}$ = mass fraction of aluminum leaving chamber unburned, averaged over agglomerate size distribution and burn time

F = instantaneous value of mass fraction unburned for a given D_{p_o}

m_D = mass fraction of $A\ell$ agglomerates with $D_{p_o} < D$

m_e = mass fraction of propellant expended

$F = F(\tau_B, \tau_R, Re, \bar{L})$

PARTICLE TRAJECTORY EQUATIONS

Gas Velocity

$$u_g = \frac{\pi V_W Z}{R_1} \cos\left[\frac{\pi}{2}\left(\frac{r}{R_1}\right)^2\right]$$

Inviscid, rotational flow solution

$$v_g = -\frac{V_w R_1}{r} \sin\left[\frac{\pi}{2}\left(\frac{r}{R_1}\right)^2\right]$$

Particle Momentum

$$\frac{d u_p}{dt} = \frac{3}{4}\frac{\rho_g}{\rho_a}\frac{C_D \Delta V}{D_p}(u_g - u_p)$$

$$\Delta V = \sqrt{(u_g - u_p)^2 + (v_g - v_p)^2}$$

$$\frac{d v_p}{dt} = \frac{3}{4}\frac{\rho_g}{\rho_a}\frac{C_D \Delta V}{D_p}(v_g - v_p)$$

Particle Burning Rate

$$\frac{D_p}{D_{p_o}} = \left[1 - \frac{kt}{D_{po}^{1.8}}\right]^{\frac{1}{1.8}} \quad \text{for } t < t_b$$

Empirical burning rate law

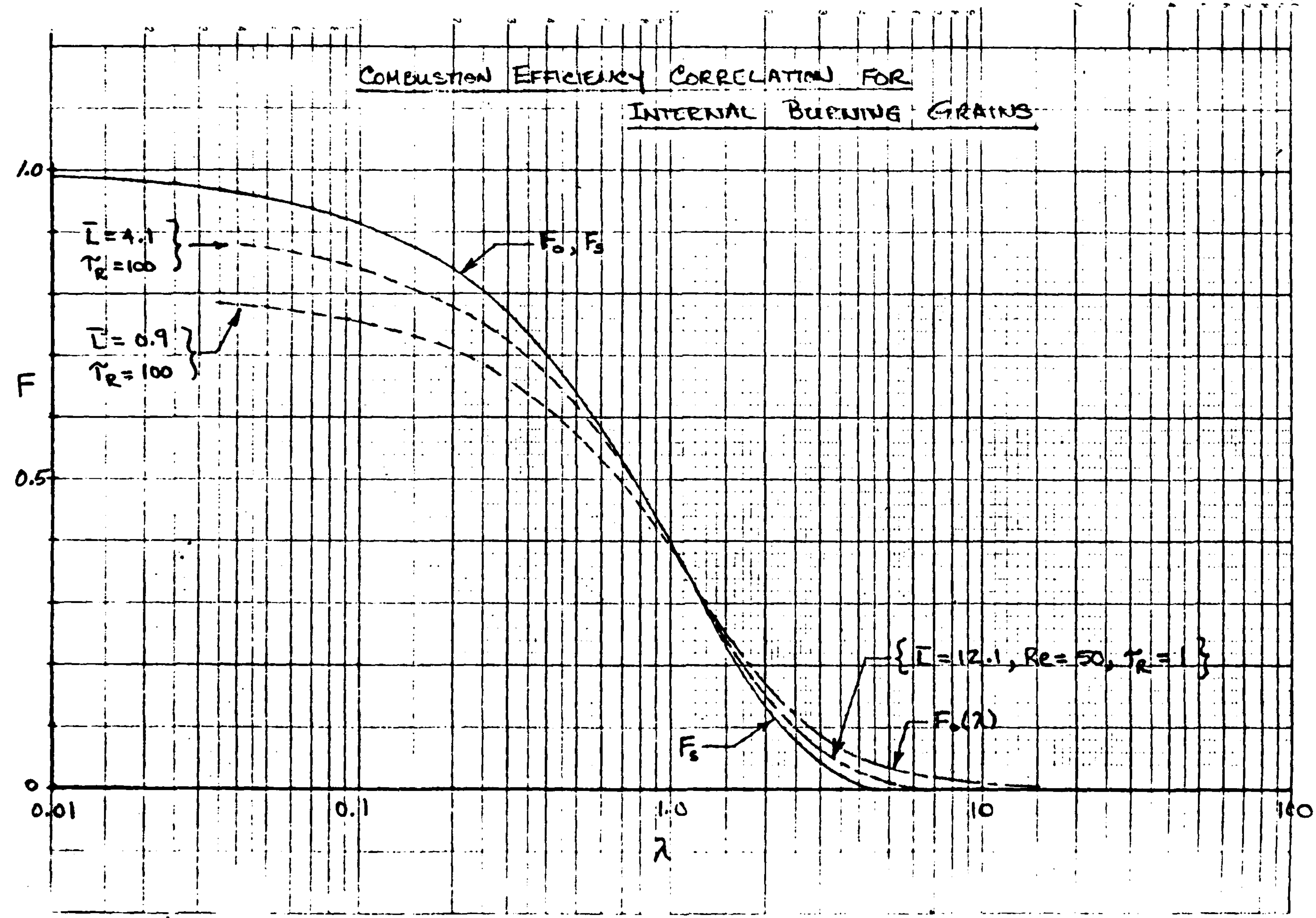
$$= \quad 0 \qquad t \geq t_b$$

DIMENSIONLESS VARIABLES CONTROLLING COMBUSTION EFFICIENCY

Variable	Definition	Physical Significance	
τ_B	$\dfrac{V_w D_{po}^{1.8}}{k}$	$\dfrac{\text{burning time}}{\text{flow time}}$	Determines zero-lag values; also influences values with lag because of influence on Dp(t).
τ_R	$\dfrac{\rho_a D_{po}^2 V_w}{R_1 \mu_g}$	$\dfrac{\text{relaxation time}}{\text{flow time}}$	Influences degree of lag; when $\tau_R \to 0$ values approach zero lag limit.
Re	$\dfrac{D_p V_w \rho_g}{\mu_g}$	$\dfrac{\text{inential forces}}{\text{viscous forces}}$	Influences degree of lag; higher Re causes less lag and shortens residence time.
$\bar{L}$	L/R_1	dimensionless motor length	Influences average particle velocity and residence time.

DEFINITION OF VARIABLES AND RANGE OF VALUES

Variable	Definition	Values
D_{p_o}	Aluminum agglomerate diameter leaving propellant surface	50 to 500 μm
V_w	Gas velocity at burning propellant surface	2 to 7 m/sec
ρ_g	Chamber gas density	2 to 7×10^{-3} g/cm^3
R_1	Effective chamber radius ($2V_c/Ab$ for noncircular ports)	0.05 to 3 m
L/R_1	Dimensionless chamber length	1 to 50
μ_g	Chamber gas viscosity	3×10^{-4} - 1×10^{-3} poise
k	Aluminum burning rate constant	0.005 - 0.05 cm$^{1.8}$/sec
ρ_a	Density of burning aluminum agglomerate	2.1 g/cm^3


COMBUSTION EFFICIENCY CORRELATION FOR
INTERNAL BURNING GRAINS
1.0
0.5
0
F
0.01
0.1
1.0
10
100
λ
$\bar{L} = 4.1$, $\tau_R = 100$
$\bar{L} = 0.9$, $\tau_R = 100$
F_o, F_s
$\{\bar{L} = 12.1, Re = 50, \tau_R = 1\}$
$F_o(\lambda)$
F_s

COMBUSTION EFFICIENCY CORRELATION

$$F = \frac{2h}{1 + \exp\,(b\lambda^{c})} \qquad (h = 1 \text{ for } F_o,\ F_s)$$

$$c = c_1 - c_2$$

$$b = 1.5318c_1 + 1.236c_2$$

$$c_1 = \frac{0.9418\,(1 + 95.83\lambda^2)}{1 + 100\lambda^2} \qquad c_2 = \frac{0.0288\lambda^4 g}{1 + 0.062\lambda^4} \qquad \begin{pmatrix} g = 1 \text{ for } F_o \\ g = 0 \text{ for } F_s \end{pmatrix}$$

$$\lambda = \alpha/\tau_B$$

$$\alpha = 1 + 0.9509\,Re^{-0.167}\,\sqrt{\tau_R}\;\bar{L}^{-0.33}\,(Re/\tau_R)^{0.135}$$

$$h = 1 + \left[\frac{0.064}{(\lambda^2 + 0.16)(1 + 86.2\,[\bar{L}/\tau_R]^{1.11})}\right]^{-1}$$

$$g = \exp\,[-17.3\,(\alpha - 1)^2]$$

MOTOR DATA FOR CALIBRATION OF ALUMINUM BURNING RATE

Motor	Propellant	D_t in	P_c psia	$\bar{\tau}$ msec	$\left(\frac{\Delta I_{sp}}{I_{sp}}\right)_{ce}$	F	k_{obs} $cm^{1.8}$ sec^{-1}	k_{corr} $cm^{1.8}$ sec^{-1}	R_k
4.8x17.3	16 Aℓ-PBAN	0.945	1200	12.4	0.0032	0.023	0.02973	0.00973	3.06
4.8x11.6	16 Aℓ-PBAN	0.945	650	8.3	0.0145	0.1015	0.02208	0.00821	2.69
4.8x8.4	16 Aℓ-PBAN	0.945	470	6.0	0.0291	0.198	0.01994	0.00751	2.66
4.8x4.3	16 Aℓ-PBAN	0.945	145	2.6	0.0662	0.421	0.01643	0.00541	3.04
3.2x5.7	16 Aℓ-PBAN	0.945	104	2.1	0.0826	0.513	0.01269	0.00463	2.74
70 lb BATES	21 Aℓ-HTPB	2.077	946	18.0	0.0027	0.0197	0.02833	0.01031	2.75
70 lb BATES	24 Aℓ-HTPB	1.904	964	21.2	0.0037	0.0240	0.02264	0.00904	2.50
70 lb BATES	27 Aℓ-HTPB	1.953	966	19.9	0.0052	0.0429	0.02291	0.00794	2.89
70 lb BATES	30 Aℓ-HTPB	1.872	1136	21.8	0.0077	0.0808	0.01689	0.00704	2.40
15 lb BATES	21 Aℓ-HTPB	1.191	934	10.5	0.0109	0.0724	0.02373	0.01031	2.30
15 lb BATES	24 Aℓ-HTPB	1.094	1001	12.3	0.0135	0.0873	0.02418	0.00904	2.67
15 lb BATES	27 Aℓ-HTPB	1.121	973	11.4	0.0124	0.0953	0.02254	0.00794	2.84
15 lb BATES	30 Aℓ-HTPB	1.070	1117	12.4	0.0142	0.1390	0.01793	0.00704	2.55

NOZZLE THROAT EROSION MODEL

Basic Approach: $\dot{r}_t = \frac{1}{\rho_m} \beta_m \dot{B}_c G C_H$

- Stanton Number from BARTZ correlation:

$$C_H = 0.023 \left(\frac{D_t G}{\mu}\right)^{-0.2} \left(\frac{C_p \mu}{\kappa}\right)^{-0.6}$$

- Effective Blowing Parameter from Correlation of GASKET and CMA results:

$$\dot{B}_c = \bar{x}_{ox} f_1(T_w) + \bar{x}_H f_2(T_w)$$

f_1 and f_2 depend on material but not on propellant

$\left.\begin{array}{l}\bar{x}_{ox} \\ \bar{x}_H\end{array}\right\}$ are sum of gas mole fractions $\left\{\begin{array}{l}CO_2,\ H_2O,\ O,\ OH,\ O_2 \\ H_2,\ H\end{array}\right.$

- Surface temperature from:

$$T_w = T_o + (0.85T_c - T_o)\left(1 - e^{-c_5 G^{0.8} t/k_m}\right)$$

TABLE 4-11 NOZZLE THROAT EROSION RATES
(Sheet 1 of 2)

Motor	Propellant	D_t, in.	$\bar{P}_c$, psia	t_a, sec	Throat Material	Average Erosion Rate, mil/sec Obs.	Calc.	Diff.	Maximum Error* mil/sec
Shuttle SRM	PBAN 86% solids 16% Aℓ	54.4	580	124.1	Carbon-phenolic	8.9	7.5	-1.4	3.3
Titan III-C Stage 0	PBAN 84% solids 16% Aℓ	37.7	546	113.7	Carbon-phenolic	4.7	6.2	1.5	2.5
Algol	PBAN 84.5% solids 17% Aℓ	12.7	450	72.3	Carbon-phenolic	6.4	6.9	0.5	1.3
SVM-7	CTPB 88% solids 15% Aℓ	3.2	600	27.0	G-90 graphite	3.5	2.4	-1.1	0.9
FW-5	PBAN 84.5% solids 16.4% Aℓ	2.04	732	33.4	G-90 graphite	2.0	3.5	1.5	0.5
70-lb BATES	HTPB 86% solids reduced smoke	1.46	1,000	2.3	ATJ graphite	2.3†	3.7‡	1.4	4.8
70-lb BATES	HTPB 90% solids 18% Aℓ	2.12	950	3.38	ATJ graphite	10.0†	8.6‡	-1.4	4.7
70-lb BATES	HTPB 90% solids 21% Aℓ	1.84	970	4.5	ATJ graphite	8.8†	10.6‡	1.8	3.1

*To achieve ±3% accuracy in P_c.

†Maximum rate inferred from difference between 15- and 70-lb BATES tests.

‡Maximum erosion rate ($T_w = T_{max}$)

TABLE 4-11 NOZZLE THROAT EROSION RATES
(Sheet 2 of 2)

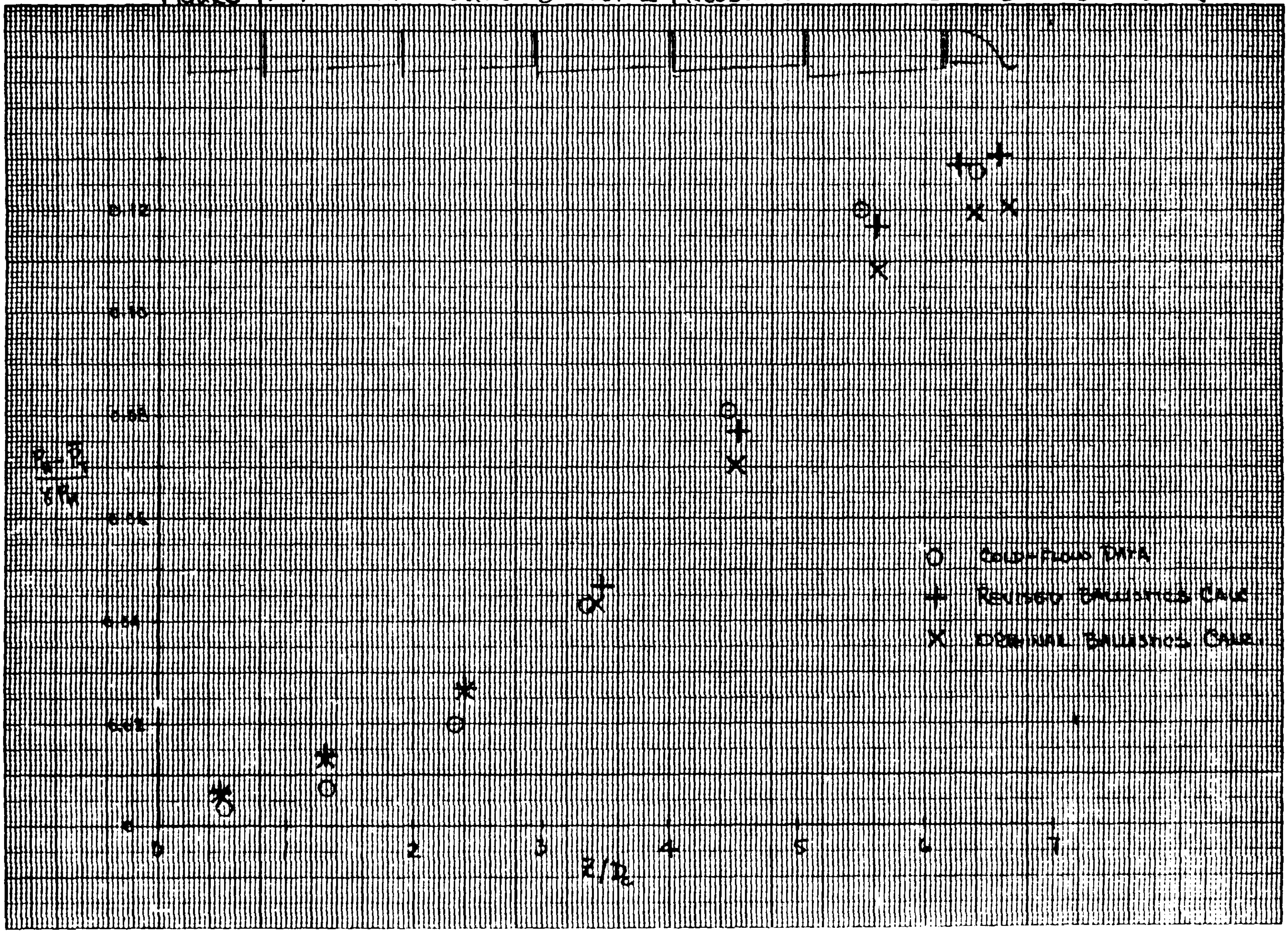
Motor	Propellant	D_t, in.	$\bar{P}_c$, psia	t_a, sec	Throat Material	Average Erosion Rate, mil/sec Obs.	Calc.	Diff.	Maximum Error* mil/sec
FW-4	PBAN 84.5% solids 16.4% Aℓ	2.28	660	31.5	ATJ graphite	3.4	2.9	-0.5	0.5
MX-SS (ADP)	PEG/FEFO 85% solids 19% Aℓ	6.92	1,250	52.2	Pyrolytic graphite	6.3	6.0	-0.3	1.0
C-4/TS (ADP)	HTPB 90% solids 18% Aℓ 25% HMX	4.04	980	43.4	Pyrolytic graphite	3.1	2.6	-0.5	0.7
IPSM DV-1	HTPB 86% solids 18% Aℓ	3.23	678	61.8	Pyrolytic graphite	0.9	1.1	0.2	0.4
IUS-LM	HTPB 86% solids 18% Aℓ	6.82	550	150.7	3-D carbon-carbon	1.8	1.8	0	0.3
CCAN-TM-3	HTPB 90% solids 18% Aℓ	1.92	1,000	23.0	3-D carbon-carbon	7.9	8.1	0.2	0.6

*To achieve ±3% accuracy in P_c.

MODIFIED PRESSURE DROP CALCULATION

PRESENT METHOD		IMPROVED SPP METHOD
1-D, COMPRESSIBLE		1-D, COMPRESSIBLE - CORRECTED FOR 2-D EFFECTS, INCLUDING COMPRESSIBLE INTERACTIONS
$\Delta P_t = \frac{\gamma}{2} M^2 \frac{\Delta \dot{m}}{\dot{m}} P_t$	MASS ADDITION $\longrightarrow$	$\Delta P_t = \frac{\gamma}{2} M^2 \frac{\Delta \dot{m}}{\dot{m}} P_t \frac{\pi^2}{8} [1 + \frac{\pi^2}{12} M^2]$ based on analysis of Flandro
$\Delta P_t = \frac{\gamma}{2} M^2 K_c P_t$	CONTRACTION LOSS $\longrightarrow$	Same
INCOMPRESSIBLE K_c FROM KAYS (1950)		K_c CORRECTED FOR COMPRESSIBILITY EFFECTS AT VENA CONTRACTA
$K_c = 0.4(1-A_2/A_1)$		$K_c = 0.4(1-A_2/A_1)(1+3.05M^4)$
		Verified by data of Roessler & Landsbaum (1971)

FIGURE 1. AXIAL DISTRIBUTION OF TOTAL PRESSURE T34D ZERO BURNBACK



SPP EROSIVE BURNING OPTIONS

OPTION

0. Erosive Burning not Considered

1. Modified Lenoir - Robillard

$$\dot{r} = \dot{r}_o + \frac{\alpha G^{0.8}}{f(D_h)} \exp\left(- \frac{\beta \rho_p \dot{r}}{G}\right) \qquad \text{Empirical } f(D_h)$$

2. Lenoir-Robillard

$$\dot{r} = \dot{r}_o + \frac{\alpha G^{0.8}}{Z^{0.2}} \exp\left(- \frac{\beta \rho_p \dot{r}}{G}\right)$$

3. Green

$$\dot{r} = \dot{r}_o \quad (1 + KM)$$

4. Saderholm

$$\dot{r} = \dot{r}_o \qquad M \leq M_{crit}$$

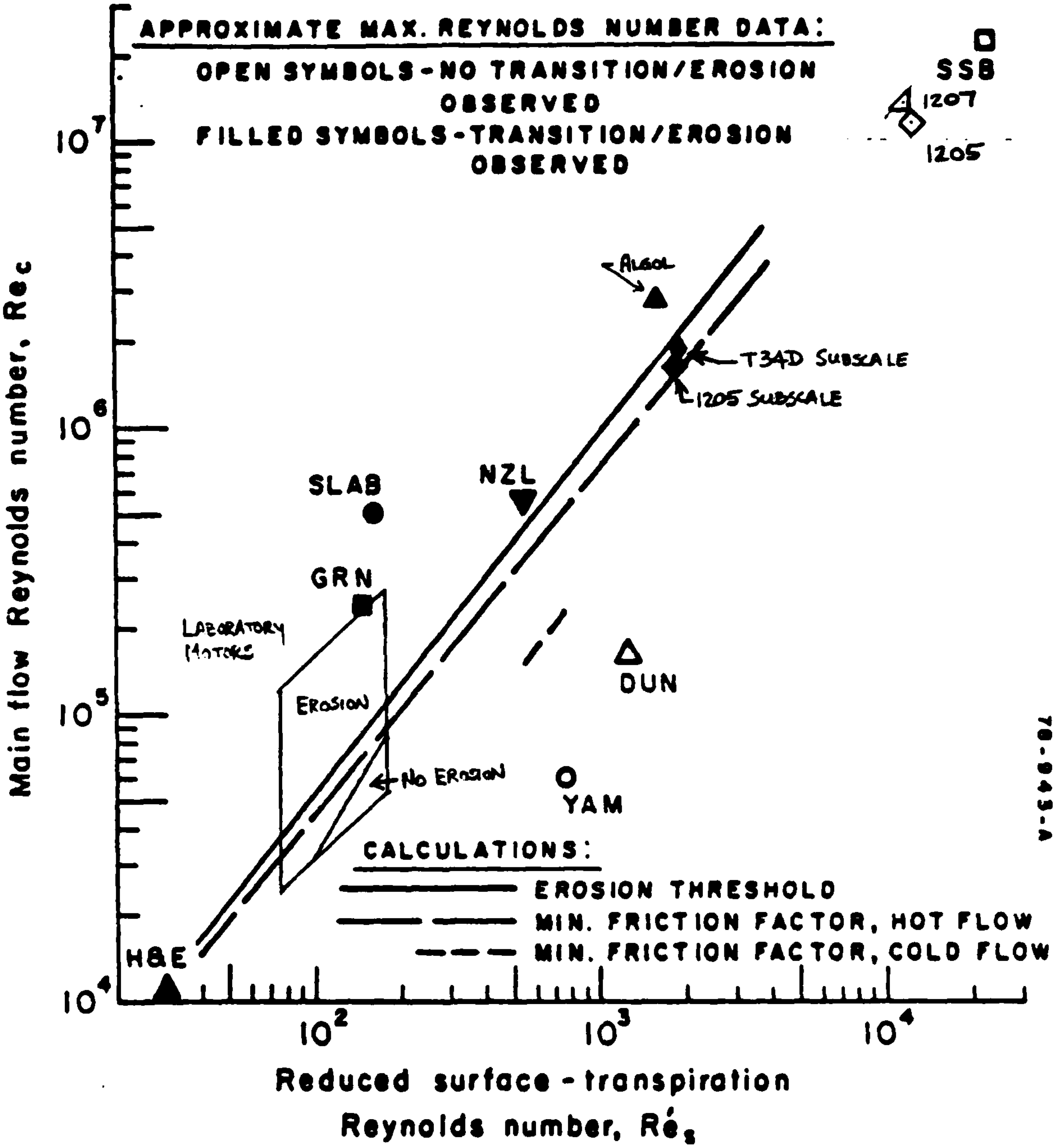
$$\dot{r} = \dot{r}_o \, (M/M_{crit})^a \qquad M_{crit} < M < 0.5$$

$$\dot{r} = 0.0093 \, (MP)^{0.71} \qquad 0.5 \leq M \leq 1$$

EROSIVE BURNING

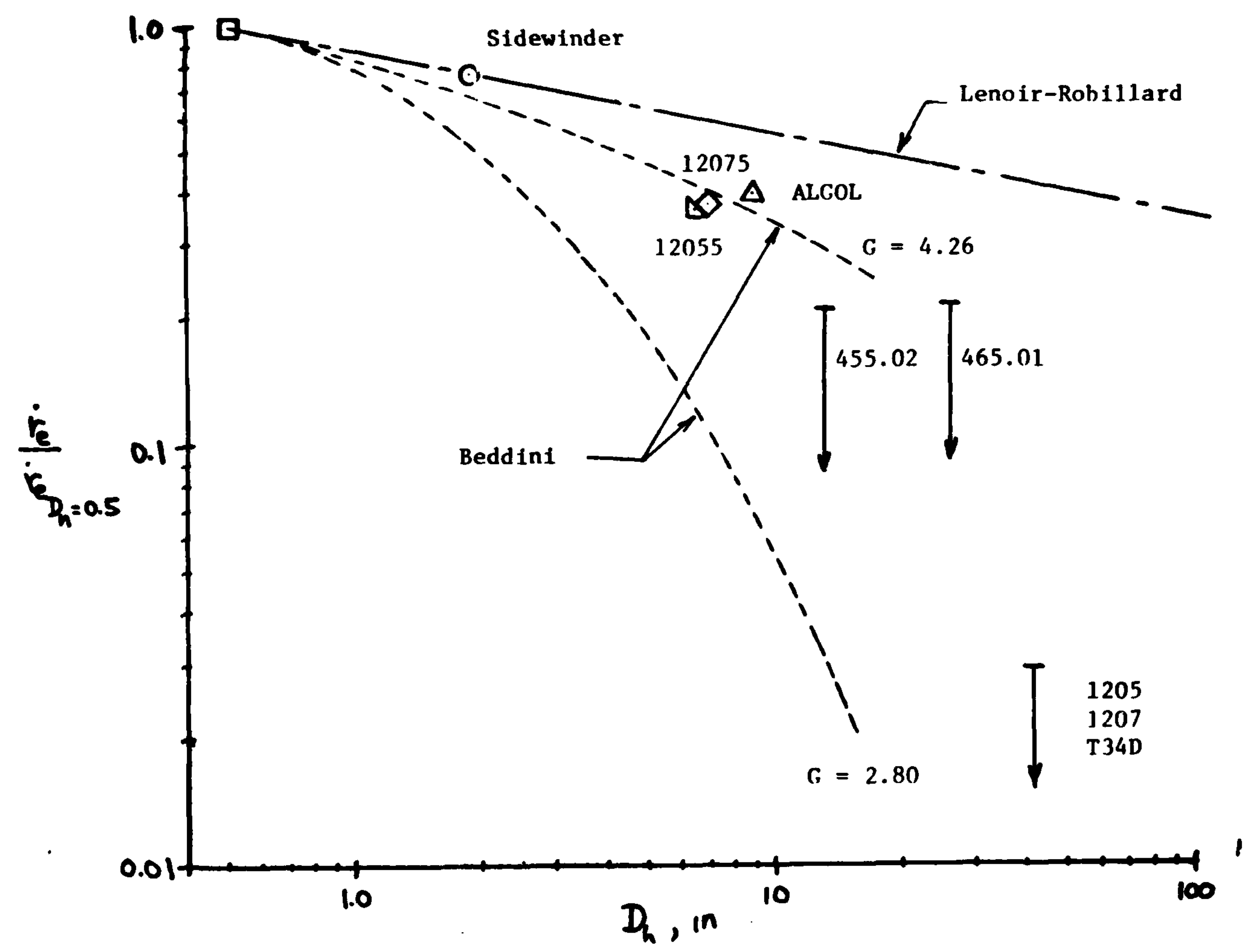
MODELING EFFORTS IN PROGRESS

APPROACH	STATUS	REMARKS
	ARAP - R. A. BEDDINI	
. Confined reacting turbulent boundary layer. . Second-order closure turbulence model. . Simplified combustion model.	. Calculations for flat plate and tubular geometry. . Established threshold criterion. . Trends agree qualitatively with observed erosive burning behavior.	. Improved physical model - has potential of explaining effect of motor scale. . Further development needed to obtain quantitative agreement. . Method of application needs to be developed.
	ARC - M. K. King	
. Bending of columnar diffusion flames. . BDP - Type of combustion model. . Effect of flow enters through mean velocity profile.	. First generation model complete. . Reasonable agreement with data for some propellants -- poor for others.	. More development needed to treat range of propellant types and verify accuracy.
	PENN. STATE - K. Kuo	
. Similar to ARAP model but with more complex combustion model.	. Model development in progress.	. Accuracy unknown.



Comparison of motor data with erosive burning threshold predicted by Beddini. Region above solid line is expected to have erosive burning.

EFFECT OF MOTOR SCALE ON EROSIVE BURNING

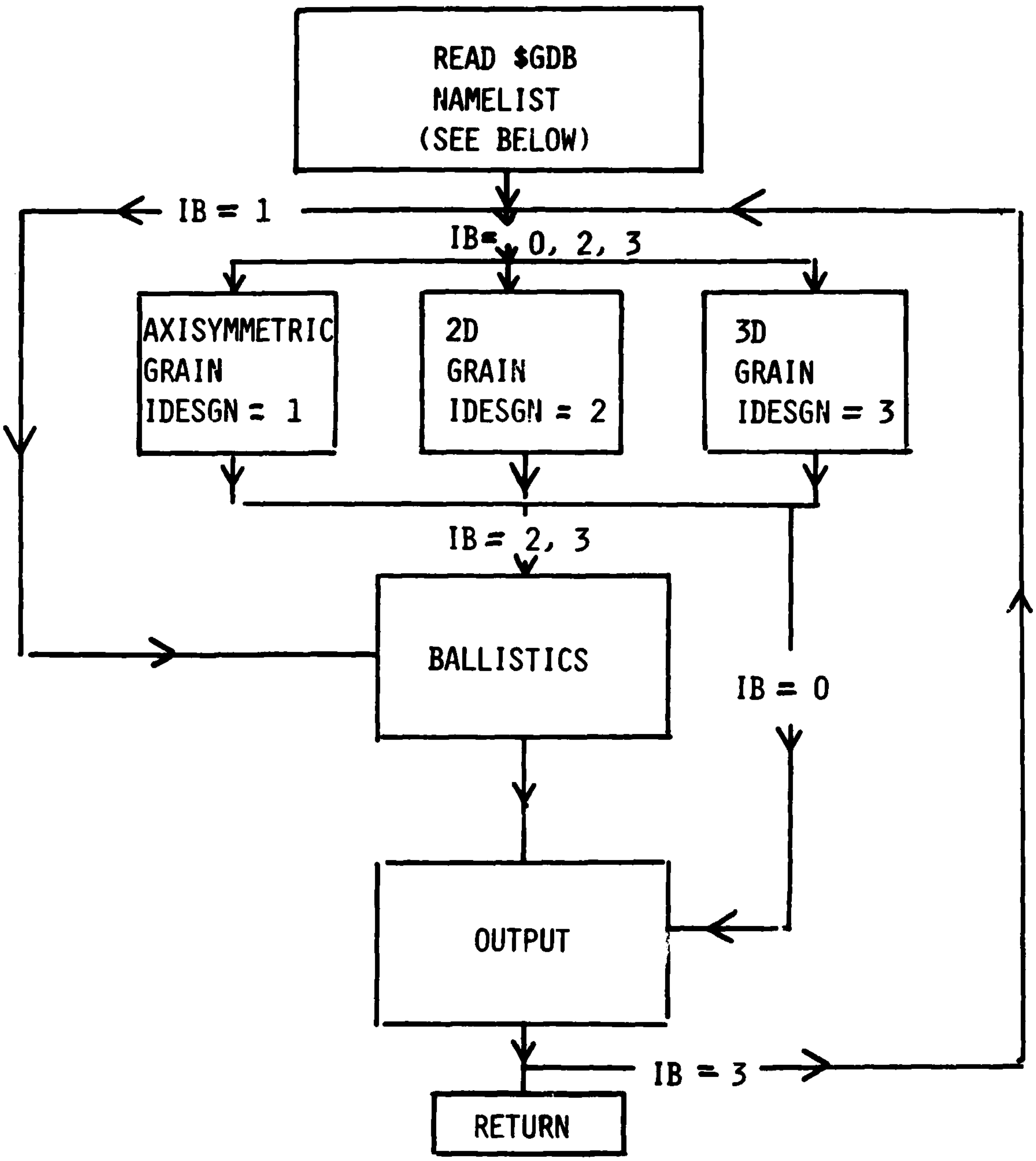


GRAIN DESIGN
AND
INTERNAL BALLISTICS MODULE

J. T. LAMBERTY

UT-CSD SUNNYVALE, CA

MAIN PROGRAM

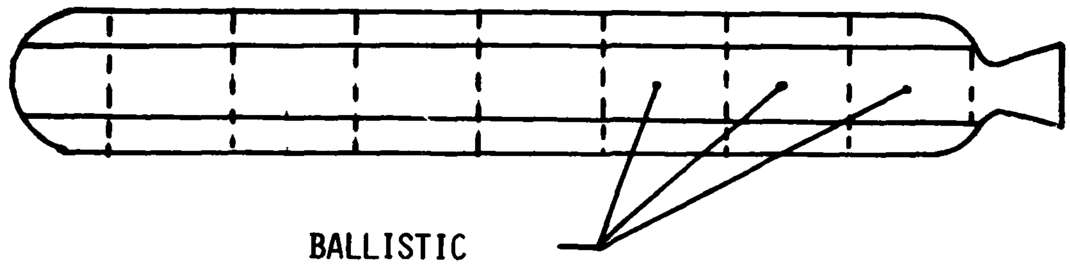


PARAMETER	VALUE	SIGNIFICANCE
IB	0	GRAIN DESIGN ONLY
IB	1	BALLISTICS ONLY
IB	2	GRAIN DESIGN & BALLISTICS
IB	3	COUPLED SOLUTION
IDESGN	1	AXISYMMETRIC GRAIN
IDESGN	2	2D GRAIN
IDESGN	3	3D GRAIN

BALLISTIC MODULE FEATURES

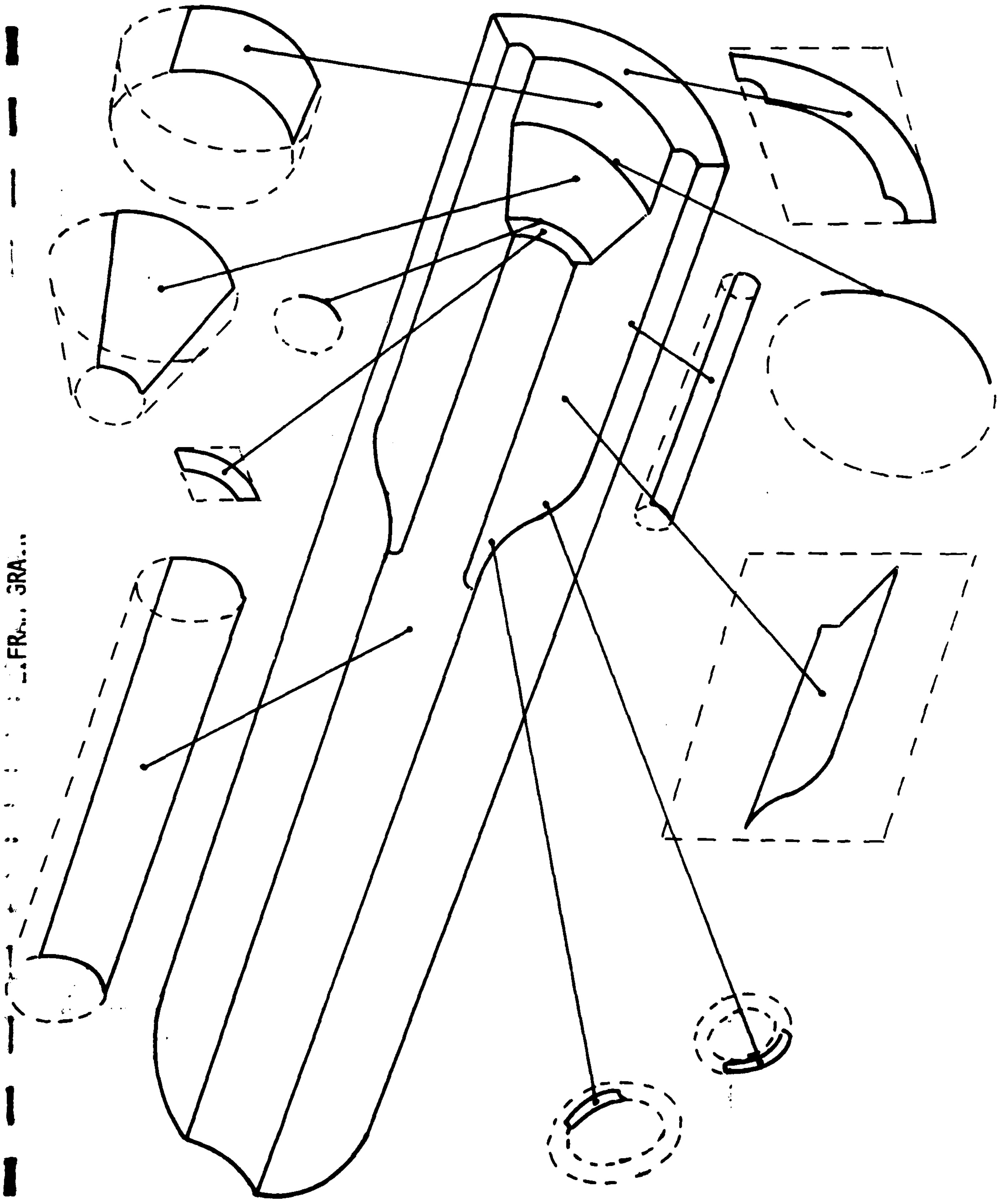
- NAMELIST INPUT
- NON-EQUILIBRIUM
  - IGNITION RISE
  - TAILOFF BLOWDOWN
  - AUTOMATIC TRANSIENT CALCULATIONS
- MULTI-PROPELLANT (50 MAX)
  - BURN RATE
  - EXPONENT
  - DENSITY
  - EROSIVE CONSTANTS
  - BRM
- THROAT EROSION OPTIONS
  - CALCULATE EROSION RATE
  - INPUT EROSION RATE TABLE
  - INPUT THROAT AREA TABLE
- EROSIVE BURNING OPTIONS
  - LENOIR ROBILLARD (LENGTH)
  - LENOIR ROBILLARD (DIAMETER)
  - GREEN
  - SADERHOLM
- 3 SURFACE AREA OPTIONS
  - INPUT
  - CALCULATED
  - COMBINATION
- SEQUENTIAL SOLUTION
- COUPLED SOLUTION
- PLOT (CAL COMP)
  - PRESSURE (AFT & FORWARD)
  - THRUST (S.L. & VAC)
  - GRAIN BURNBACK
- BURNING RATE OPTIONS
  - $\dot{r} = cP^n$
  - $\dot{r}$ - Pc TABLE
  - $\dot{r}$ - WEB TABLE
  - $\dot{r} = \dot{r} \times$ BRM
- IGNITER FLOW RATE INPUT

BALLISTIC ELEMENT METHOD



ELEMENT DESCRIPTION		ADVANTAGES
LENGTH (ACCURACY NOT CRITICAL)	MIN. REQUIRED	MULTI-PROPELLANT
SURFACE AREA VS WEB TABLE	MIN. REQUIRED	BATCH BURN RATES
PORT AREA VS WEB TABLE	MIN. REQUIRED	SELECTIVE BRM (BARF)
BURN RATE, EROSIVE BURNING CONSTANTS		SINGLE ELEMENT OPTION
BURN RATE MODIFIER TABLE		
LOSS COEFFICIENT		
DENSITY		

```
$BEPS APORT = 1, ABURN = 3, LM = 10, R1000 = .4, BRMULT = 1, $END
```



LIFRAM GRAIN DESIGN FILE

```
100  $GDB IB=0,IDESGN=3,ILIST=0,$END

200           IRR BOOSTER/ 4 FIN FINOCYL DAK 1/8/80

300  $CASE ZR=0.,0., .08,1.0, .1,1.3, .15,1.6, .2,1.92, .3,2.2, .42,2.5,
400       .52,2.8, .68,3.08, .8,3.38, 1.0,3.63, 1.25,3.9, 1.65,4.08,
500       1.70,4.102, 42.88,4.102, $END
600  $INPUT1 JN=13, JN1=12, PMAX=45,$END  # OF SURFACES AND ANGLE OF SYMMETRY

700  $INPUT3 DELTA=28*.1,5*.01,EP3=3.,$END WEB STEPS AND ACCURACY

800  $INPUT5 NSFC=1,ITYPE=2,IANGLE=1,THETA=0.,PHI=0.,
900       X=.79,Y=0.,Z=.5,R=.79,.5,UMIN=0.,UMAX=45.,
1000      VMIN=-65.,VMAX=0.,$END HEAD FILLET TORUS
1100  $INPUT5 NSFC=2,ITYPE=4,X=0.,0.,Y=0.,0.,Z=.5,29.88,R=1.29,
1200      UMIN=0.,UMAX=45.,VMIN=0.,VMAX=29.38,$END MAIN CYLINDER
1300  $INPUT5 NSFC=3,ITYPE=2,IANGLE=1,X=4.102,Y=0.,Z=29.88,
1400      THETA=90.,PHI=90.,R=3.185,.375,UMIN=90.,UMAX=134.,
1500      VMIN=0.,VMAX=180.,$END FIN TORUS 1
1600  $INPUT5 NSFC=4,ITYPE=2,IANGLE=1,X=-2.325,Y=0.,Z=36.09,THETA=90.,
1700      PHI=90.,R=5.752,.375,UMIN=-90.,UMAX=-46.,VMIN=0.,
1800      VMAX=180.,$END FIN TORUS 2
1900  $INPUT5 NSFC=5,ITYPE=4,X=3.425,3.425,Y=0.,0.,Z=36.09,42.88,
2000       R=.375,UMIN=0.,UMAX=90.,VMIN=0.,VMAX=8.,
2100       $END SMALL FIN GROOVE CYLINDER
2200  $INPUT5 NSFC=6,ITYPE=3,X=0.,Y=.375,Z=29.88,IANGLE=1,THETA=90.,
2300      PHI=90.,UMIN=-14.,UMAX=0.,VMIN=-3.425,VMAX=0.,$END  FIN SIDE PLANE
2400  $INPUT5 NSFC=7,ITYPE=4,X=0.,0.,Y=0.,0.,Z=29.88,39.93,R=1.29,
2500       UMIN=0.,UMAX=45.,VMIN=0.,VMAX=11.,$END SECOND CYLINDER
2600  $INPUT5 NSFC=8,ITYPE=-3,X=0.,Y=0.,Z=39.93,IANGLE=1,THETA=0.,
2700       PHI=0.,UMIN=1.29,UMAX=1.71,VMIN=.912,VMAX=1.210,
2800       $END NOZZLE VERT PLANE 1
2900  $INPUT5 NSFC=9,ITYPE=2,IANGLE=1,THETA=0.,PHI=0.,X=0.,Y=0.,Z=39.93,
3000       R=1.71,0.,UMIN=0.,UMAX=45.,VMIN=-90.,VMAX=49.,
3100       $END NOZZLE CORNER TORUS 1
3200  $INPUT5 NSFC=10,ITYPE=5,X=0.,0.,Y=0.,0.,Z=39.93,41.98,R=1.71,3.5,
3300        UMIN=0.,UMAX=45.,$END NOZZLE CONE
3400  $INPUT5 NSFC=11,ITYPE=2,IANGLE=1,THETA=0.,PHI=0.,X=0.,Y=0.,Z=41.98,
3500       R=3.5,0.,UMIN=0.,UMAX=45.,VMIN=-41.,VMAX=0.,
3600       $END NOZZLE CORNER TORUS 2
3700  $INPUT5 NSFC=12,ITYPE=4,X=0.,0.,Y=0.,0.,Z=41.98,42.88,R=3.5,UMIN=0.,
3800       UMAX=45.,VMIN=0.,VMAX=2.,$END NOZZLE CYLINDER
3900  $INPUT5 NSFC=13,ITYPE=-3,X=0.,Y=0.,Z=42.88,IANGLE=1,THETA=0.,PHI=0.,
4000       UMIN=3.5,UMAX=4.102,VMIN=0.,VMAX=2.90,$END NOZZLE END PLANE 2
#
```

LIFRAM BALLISTIC FILE

```
100  $GDB IB=1,$END
200 IRRFIN        IRR BOOSTER +145 +3SIG 1/4/80

300  $BALPAN BT=1.96,PIN=25.,PFINAL=16.,WEB=2.81,VIN=349.24,ETA=.9348,
400       R1000=.7938,NEXP=.4,RG=49.97,CSTAR=5057.78,RHOP=.0661,GAM=1.13,TF=6623.,
500       DE=6.96,PA=14.7,PERCNT=10.,EBTYPE=1,NBS=0,NPT=2,NN=19,BETA=70.,PLT=2,$END

600  $PTIME XY=0.,.01, .6,.02, DTAIL=.005,STIME=10,$END

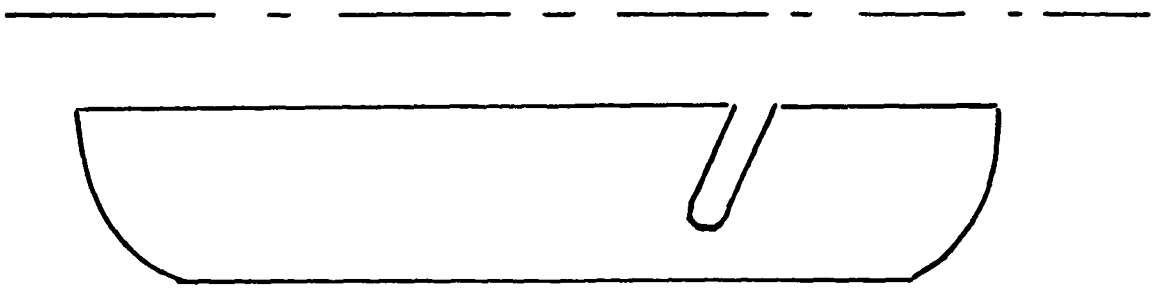
700  $PLOTTS IPLOT=1,1,0,0,PSCALE=.3,JPLOT=1,$END

800  $EROS KODE=7,XY=0.,0., .05,0., .1,25., .15,31., .5,32.3, 1.,33.5, 1.5,34.8,
900      2.0,36.1,2.6,37.,2.95,35.3, 3.05, 0.,$END

1000  $APORT RPORT=1.29,$END
1100  $APORT XY=0.,12.52, 2.81,52.81, $END

1200  $BEPS ABURN=1,APORT=1,ALFA=.15,LM=.5,$END HEAD FILLET TORUS
1300  $BEPS ABURN=2,APORT=1,ALFA=.15,LM=5.88,$END MAIN CYLINDER
1400  $BEPS ABURN=2,APORT=1,ALFA=.15,LM=5.88,$END 5 ELEMENTS OF 1 SURFACE
1500  $BEPS ABURN=2,APORT=1,ALFA=.15,LM=5.88,$END
1600  $BEPS ABURN=2,APORT=1,ALFA=.15,LM=5.88,$END
1700  $BEPS ABURN=2,APORT=1,ALFA=.15,LM=5.88,$END
1800  $BEPS ABURN=3,APORT=2,ALFA=.15,LM=2.,$END FIN TORUS 1
1900  $BEPS ABURN=4,APORT=2,ALFA=.15,LM=4.,$END FIN TORUS 2
2000  $BEPS ABURN=5,6,7,APORT=2,ALFA=.15,LM=1.6,$END 5 ELEMENTS OF 3 SURFACES
2100  $BEPS ABURN=5,6,7,APORT=2,ALFA=.15,LM=1.6,$END FIN GROOVE CYLINDER,
2200  $BEPS ABURN=5,6,7,APORT=2,ALFA=.15,LM=1.6,$END SIDE PLANE,
2300  $BEPS ABURN=5,6,7,APORT=2,ALFA=.15,LM=1.6,$END AND TOP CYLINDER
2400  $BEPS ABURN=5,6,7,APORT=2,ALFA=.15,LM=1.6,$END
2500  $BEPS ABURN=8,APORT=2,LM=.1,$END NOZZLE VERT PLANE 1
2600  $BEPS ABURN=9,APORT=2,LM=.2,$END NOZZLE CORNER TORUS 1
2700  $BEPS ABURN=10,APORT=2,LM=2.05,$END NOZZLE CONE
2800  $BEPS ABURN=11,APORT=2,LM=.2,$END NOZZLE CORNER TORUS 2
2900  $BEPS ABURN=12,APORT=2,LM=.9,$END NOZZLE CYLINDER
3000  $BEPS ABURN=13,APORT=2,LM=.1,$END NOZZLE PLANE 2
N
```

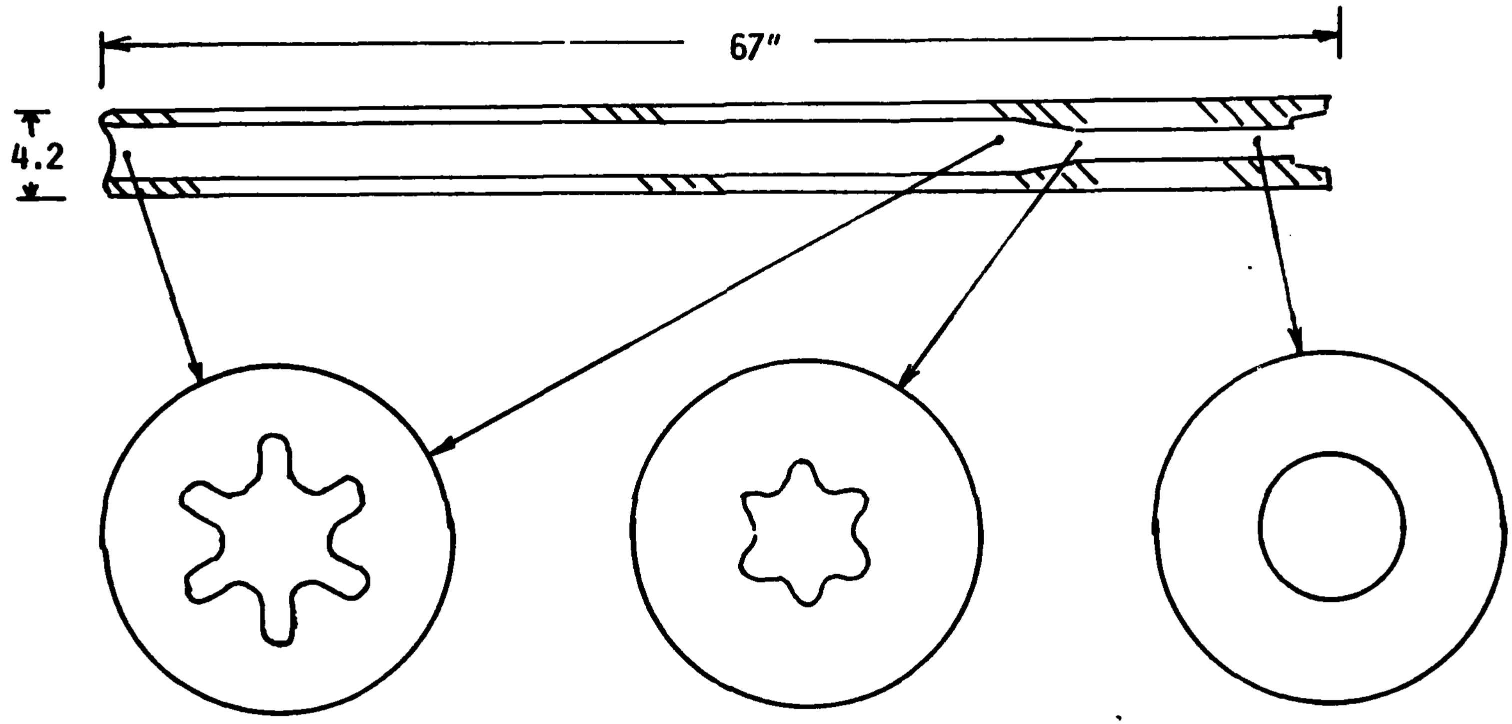
<u>AXISYMMETRIC GRAIN</u>



Set up for Grain Design and Ballistics (Sequential Solution)

```
100  $GDB IB=2,IDESGN=1,$END
200 TEST CASE FOR AXISYMMETRIC GRAIN
300  $CASE ZR=0,2, 0,5, 1,6, 20,6, 21,5, 21,2,$END
400  $GRAIN ZR=0,2, 15,2, 14,4, 15,4, 16,2, 21,2,
500    ARC=0,0,1,0,0,$END
600  $STEP DELTA=22*.2,$END
700               AXISYMMETRIC TEST CASE
800  $BALPAM DT=1.13, PIN=18, WEB=4, VIN=251, ETA=.96, R1000=.395,
900    NEXP=.25,  RG=56, CSTAR=5266,RHOP=.063, GAM=1.18, TF=6100,
1000   EIN=8, BETA=70, PA=14.7, PERCNT=10, EBTYPE=1, NM=3, NBS=0,
1100   PFINAL=16,$END
1200  $PTIME XY=0,.02,  .1,.1,  .2,.2,  DTAIL=.02, DURATN=20, STIME=1,$END
1300  $EROS KODE=7, XY=0,2, 50,2,$END
1400  $BRMULT XY=0,1.5,  4,1.5,$END
1500  $BEPS ABURN=1, APORT=1, BRMULT=1, LM=15,$END
1600  $BEPS ABURN=2,3,4, APORT=1, LM=1,$END
1700  $BEPS ABURN=5, APORT=T,BRMULT=1,$END
N
```

SIDEWINDER GRAIN




```
100  $GDB IB=0, IDESGN=2,$END
200   SIDEWINDER
300  $MAIN2D NC=5,NAB=1,1,1,1, DWEB=20*.1,$END
400  $CASE ZR=0,2.357, 71,2.357,$END
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600  $GRAIN TYPE=2,N=6,Z=54.295,R=2.357,W=.9115,R1=.214,R2=.195,ETA=30,PSI=30,$END
700  $GRAIN TYPE=2, N=6,Z=57.545,R=2.357,W=1.382,R1=.214,R2=.195,ETA=60,PSI=30,$END
800  $GRAIN TYPE=5,R=2.357,Z=63.575,XY=.9375,0,  .66281,.66281, 0,.9375,
900    DEG=90, ARC=-1,NEGBRN=0,0,$END
1000  $GRAIN TYPE=5,R=2.357,Z=67.8,XY=.9375,0,  .66281,.66281, 0,.9375,
1100    ARC=-1, NEGBRN=0,0,$END
N
```

SIDEWINDER BALLISTICS FILE

```
L
100  $GDB IB=1,$END
200 SIDEW2        SIDEWINDER ALFA=.15, 28 MODULES
300  $BALPAM R1000=.27, NEXP=.3, RHOP=.061, VIN=195, RG=57, CSTAR=5070, GAM=1.18,
400  TF=5600, BETA=70, PIN=200, PFINAL=16, EBTYPE=1, PERCNT=10, WEB=1.4, DT=1.668,
500   DE=3.2816, NM=28, ETA=.96,PA=14.7,$END
600  $PTIME XY=0,.01, .1,.1, .5,.5, DTAIL=.02, STIME=1,$END
700  $EROS KODE=7, XY=0,5,  15,5,$END
800  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
900  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
1000  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
1100  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
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1900  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
2000  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
2100  $BEPS APORT=1, ABURN=1, ALFA=.15, LM=2.62,$END
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3500  $BEPS APORT=4, ABURN=4, ALFA=.15,LM=2.1,$END
3600 END
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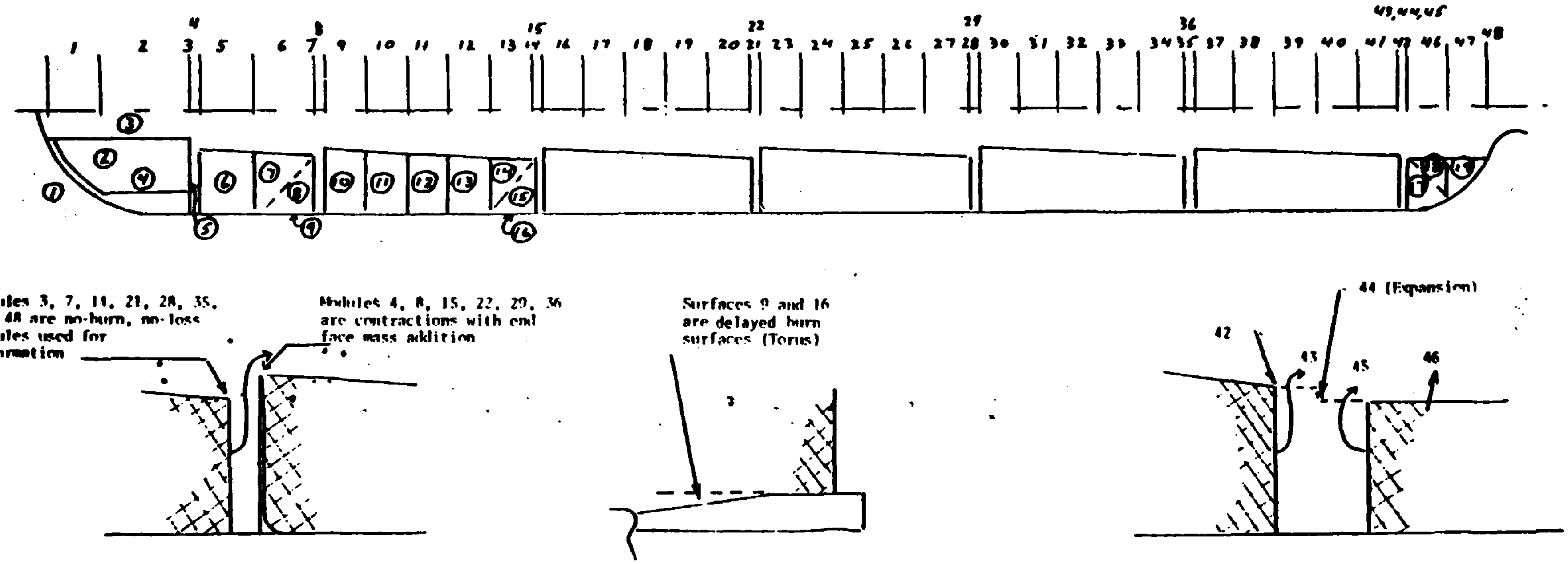
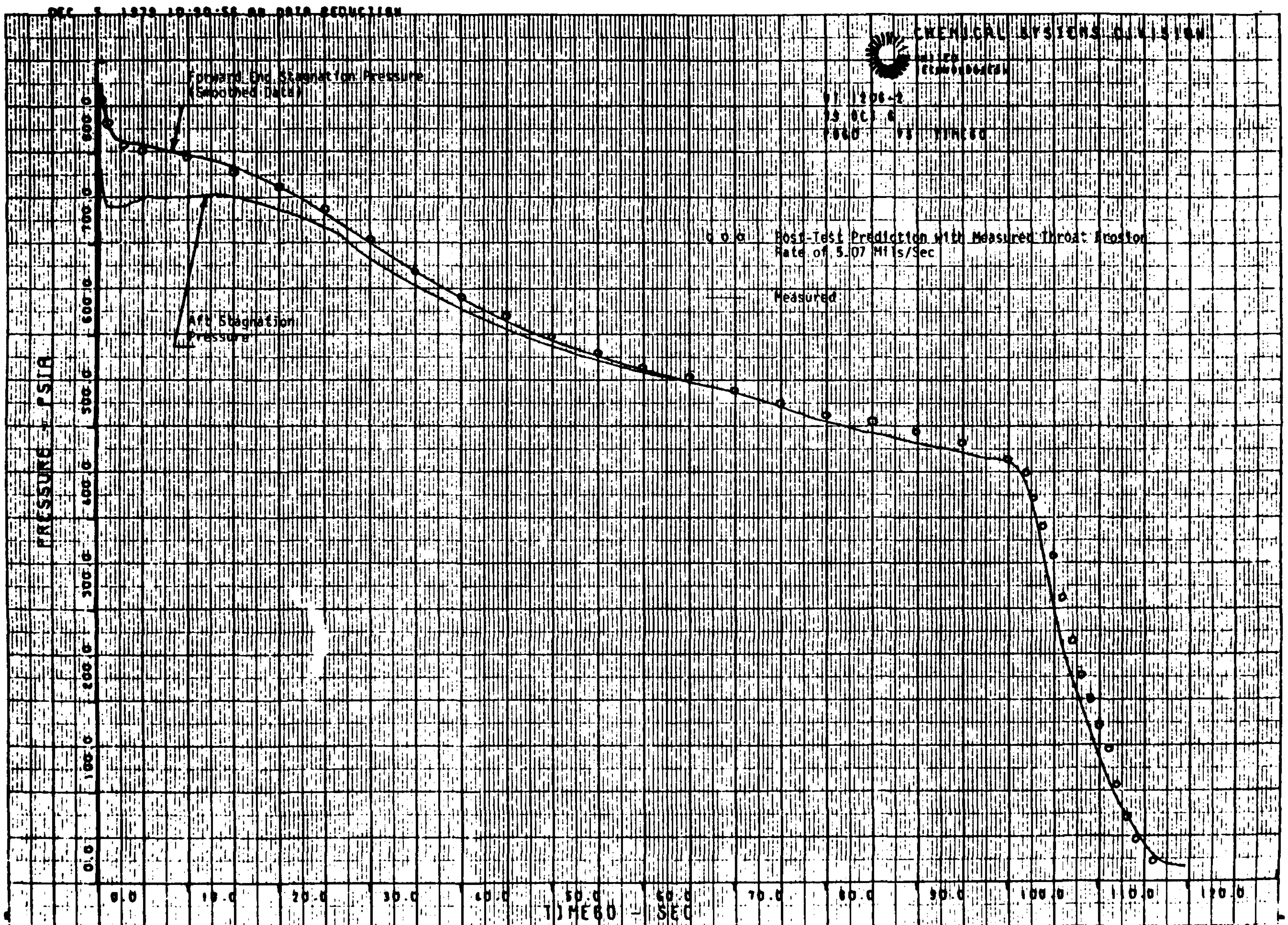
BALLISTIC MODULE AND SURFACE AREA LOCATION

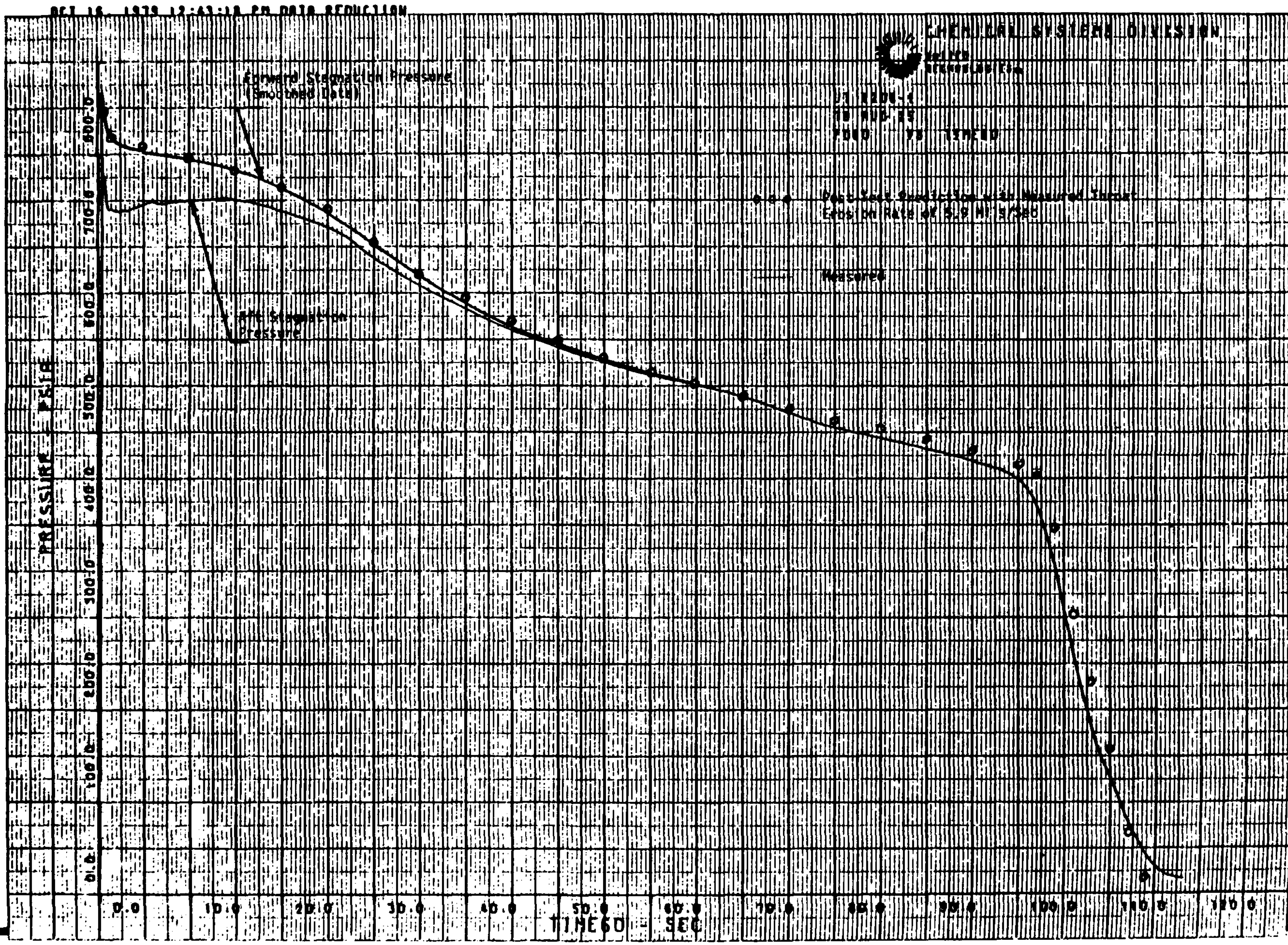
O DENOTES SURFACE AREA



Aft Closure Region

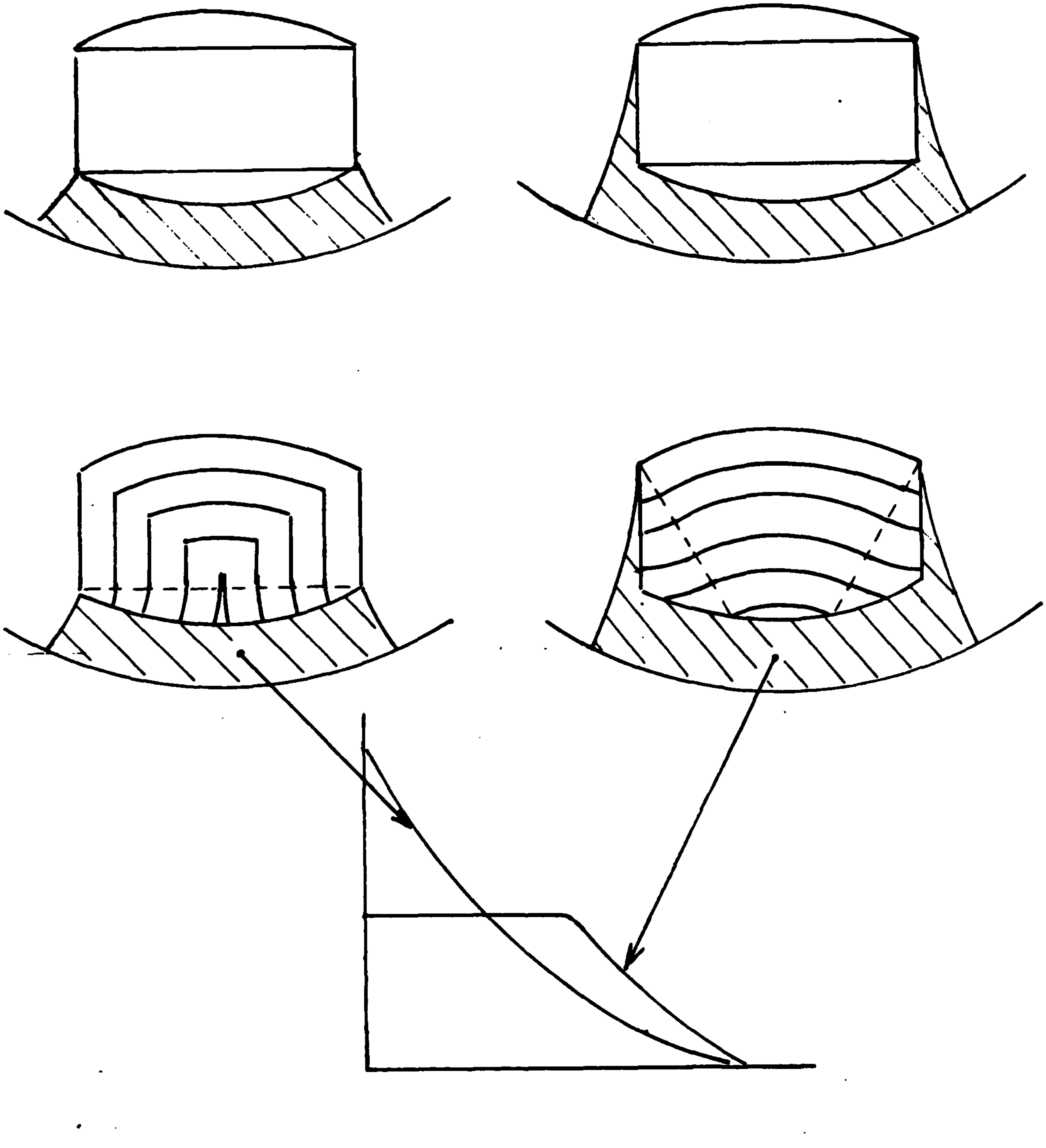


Forward and Aft Stagnation Pressure Versus Time, 1206-2, 60°F

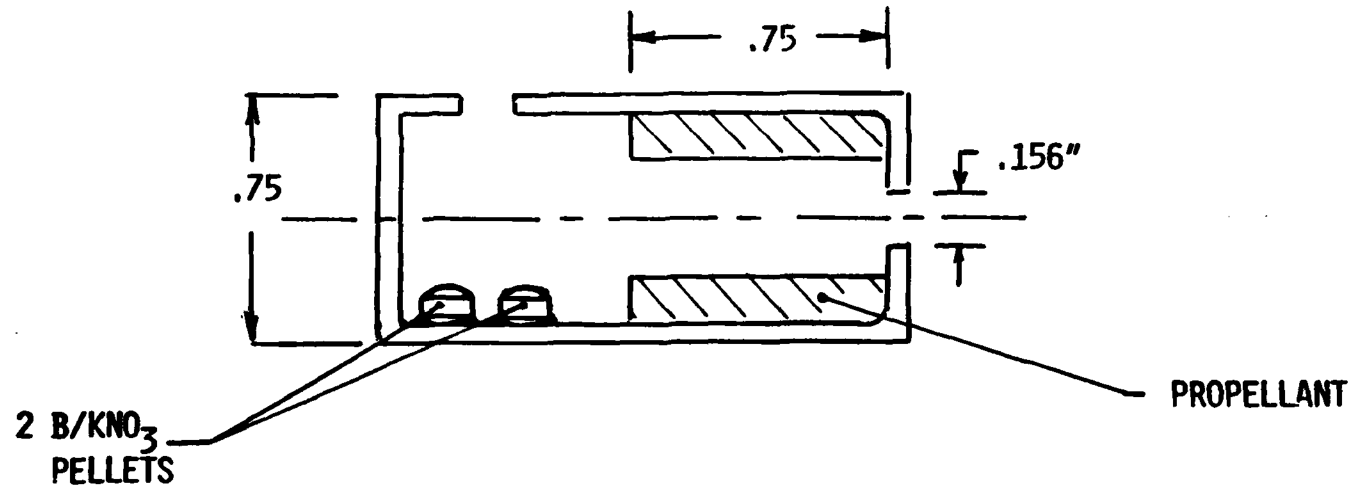


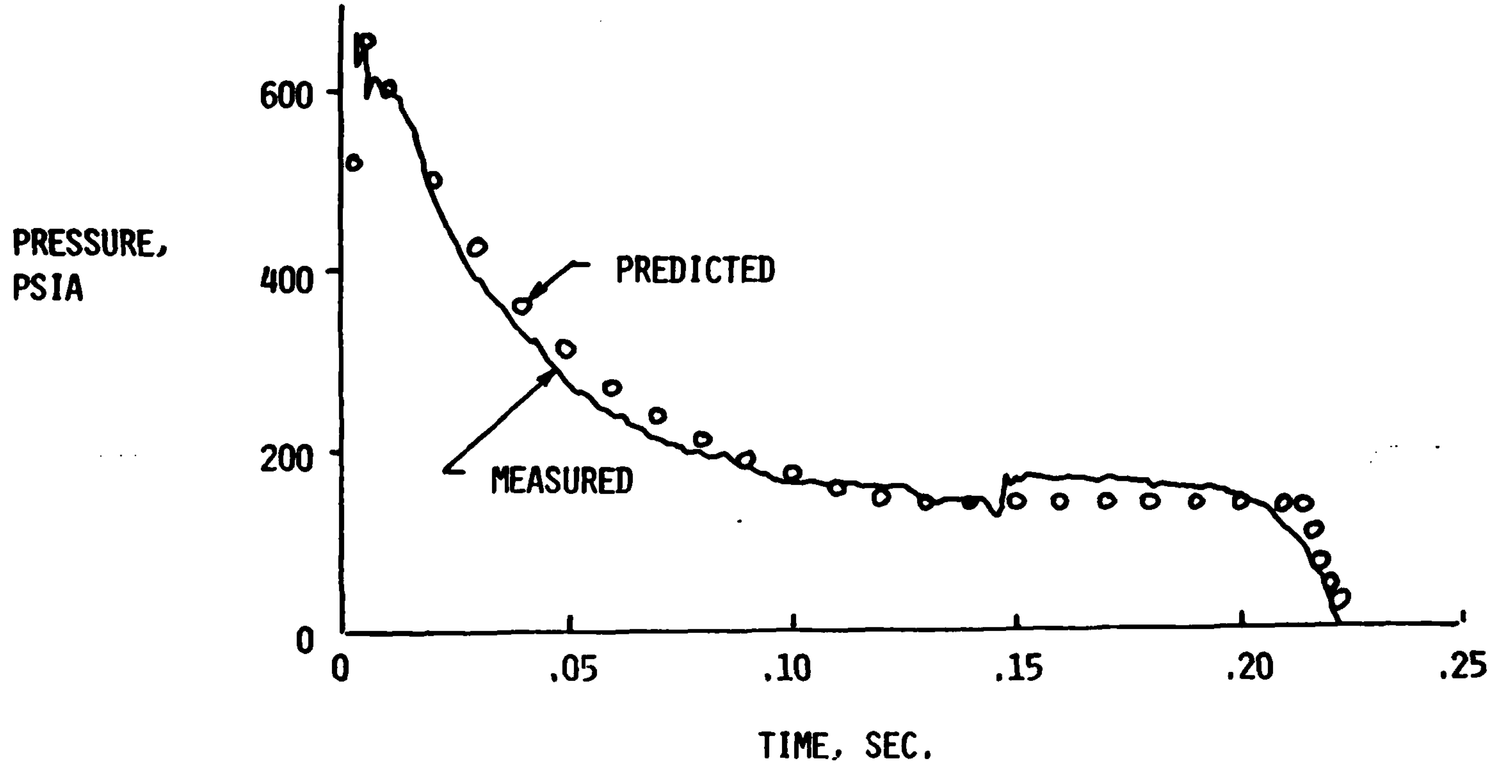
Aft and Forward Pressure Vs Time, 1206-1, 60°F

B/KNO_3 PELLET



IGNITER MODELING





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ONE DIMENSIONAL THREE-PHASE REACTING FLOW WITH MASS TRANSFER BETWEEN PHASES

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FEBRUARY 1980

PREPARED FOR:

JANNAF INTERAGENCY PROPULSION COMMITTEE
PERFORMANCE STANDARDIZATION SUBCOMMITTEE
FEBRUARY 14-15, 1980
SACRAMENTO, CALIFORNIA

INTRODUCTION

GENERAL

This is a summary of the work accomplished on Air Force Contract F04611-78-C-0011. A computer program was developed by KVB in 1973 to analyze one-dimensional reacting gas-particle flows primarily involving coal combustion. This program was developed from experience gained in prior work on rocket engines and has been re-converted for application to two phase flow in rocket motors during this contract.

The purpose of the current project was to further develop the existing computer program to incorporate additional particle size change mechanisms that are of importance in improving the ability to predict rocket motor performance. Also the program was modified to simplify the input required that is specific to rocket motor performance prediction.

All analytical work was performed at KVB, Inc., Tustin, CA. Computer programming, coding, and computation was performed by KVB with the assistance of Software and Engineering Associates (SEA), Santa Ana, CA, acting as consultants to KVB. Dr. Cye Waldman served as a consultant to KVB performing the literature survey, and selection and development of several of the size change models.

OBJECTIVE

The objective of this program is to improve the ability to predict the effect of two and three phase flow losses on the performance of solid propellant motors. The improved prediction capability is obtained by the development of the analytical capability to predict particle and droplet size change mechanisms in a reacting solid rocket nozzle flow.

SCOPE

Five program phases comprised (1) a literature search concerning particle formation, size change mechanisms, and heterogeneous gas/particle reactions; (2) selection of size change models and three-phase flow reacting gas/particle coupling equations; (3) coding of the numerical solution; (4) verification and documentation of the code; and (5) preparation of a final report.

One-dimensional nozzle flow with area change was assumed in order that the major effort could be directed to accurately modeling the physics of particle and droplet formation and size change mechanisms. The overall accuracy goal was to obtain specific impulse predictions of condensed phase particle effects to within ± 1/3% (1 sec).

The particle models were developed to account for particle agglomeration, droplet breakup, vaporization and sublimation, melting and solidification, and condensation, and reactions that occur both in the gas phase and heterogeneously on particle surfaces.

Ten particle sizes of a single class or different classes are accommodated by the program. Each class is capable of independent composition, phase, and size specification.

The reacting gas/particle conservation equations solved account for velocity and thermal lags between the droplets/particles and the gas phase including radiative and convective heat transfer to and from the particles/droplets.

The computer program calculates the entire nozzle flow field from the nozzle entrance to the exit plane. All initial conditions are specified at the nozzle entrance including automatic techniques to select the initial particle or droplet species

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and size distributions. The computation is self-contained requiring specification of the propellant system, motor operating conditions, chemical species data, and nozzle geometry. The computer program is designed to run with a minimum of input data.

The program has provision for solution of frozen equilibrium, and nonequilibrium conditions as a means of comparing theoretical specific impulse with predicted specific impulse losses due to three-phase flow effects.

The program will accommodate propellant mixtures that contain the following elements: carbon, hydrogen, oxygen, nitrogen, fluorine, chlorine, aluminum, beryllium, boron, magnesium, zirconium, and iron. Propellant formulations of primary interest to be analyzed in detail have been those that contain ammonium perchlorate (NH_4ClO_4) and aluminum with an N-F type binder. Particular attention has been given to those reactions between species containing aluminum, fluorine, and oxygen which are predominant in particle size change mechanisms in the formulations including reactions that form AlF, HF, OH, and Al_2O_3.

The overall OD3P program consists of two major programs. The primary program is the one-dimensional three-phase reacting gas-particle kinetic program. For reference to theoretical performance and as a means of obtaining starting conditions for the three-phase program, a one-dimensional equilibrium program has been merged into the three-phase program. This equilibrium program is designated herein as ODE (One-Dimensional Equilibrium). The ODE part of OD3P is essentially identical to current NASA and Air Force versions of this. ODE has been revised slightly to write an output file containing data needed to start the three-phase program.

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COMPUTER PROGRAM STRUCTURE

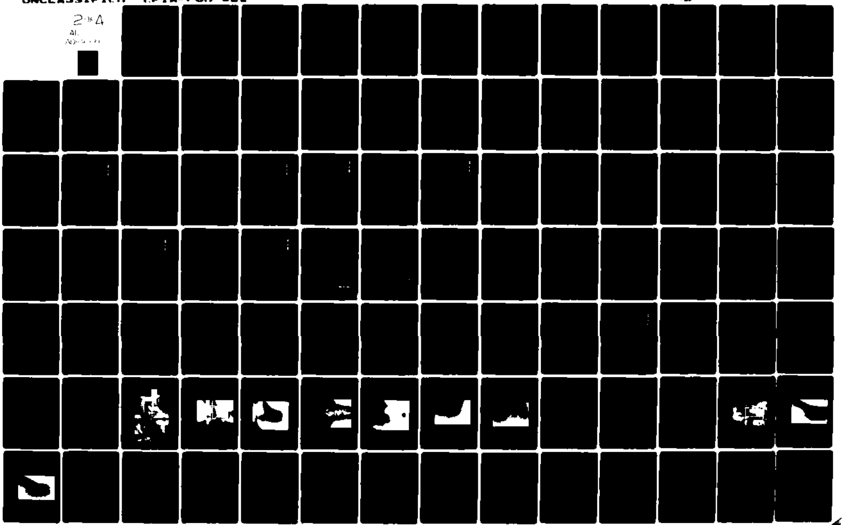
To integrate the one-dimensional gas-particle equations it is necessary to specify all variables at the starting position, furnish thermodynamic data for all species to be considered, define the desired independent variable (temperature, pressure or area) as a function of downstream position, specify integration step and output print controls, provide a set of elementary kinetic reactions for the gas phase species, and specify the number of particle groups, their size, concentration, composition, and the size change mechanisms to be considered. The program includes a plotting routine which requires specification of the variables to be plotted.

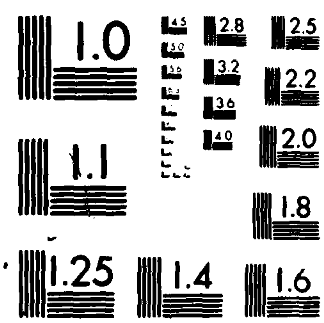
The major program functions are arranged in seven modules; Figure 1 shows the functional arrangement of the modules in relation to the input deck and several data storage files. Figure 2 lists all of the 102 subroutines in each module.

Table 1 lists the input deck sections required to run the program. Table 2 shows the format of the input deck. Table 3 lists the program output parameters printed at print stations specified by position or area ratio.

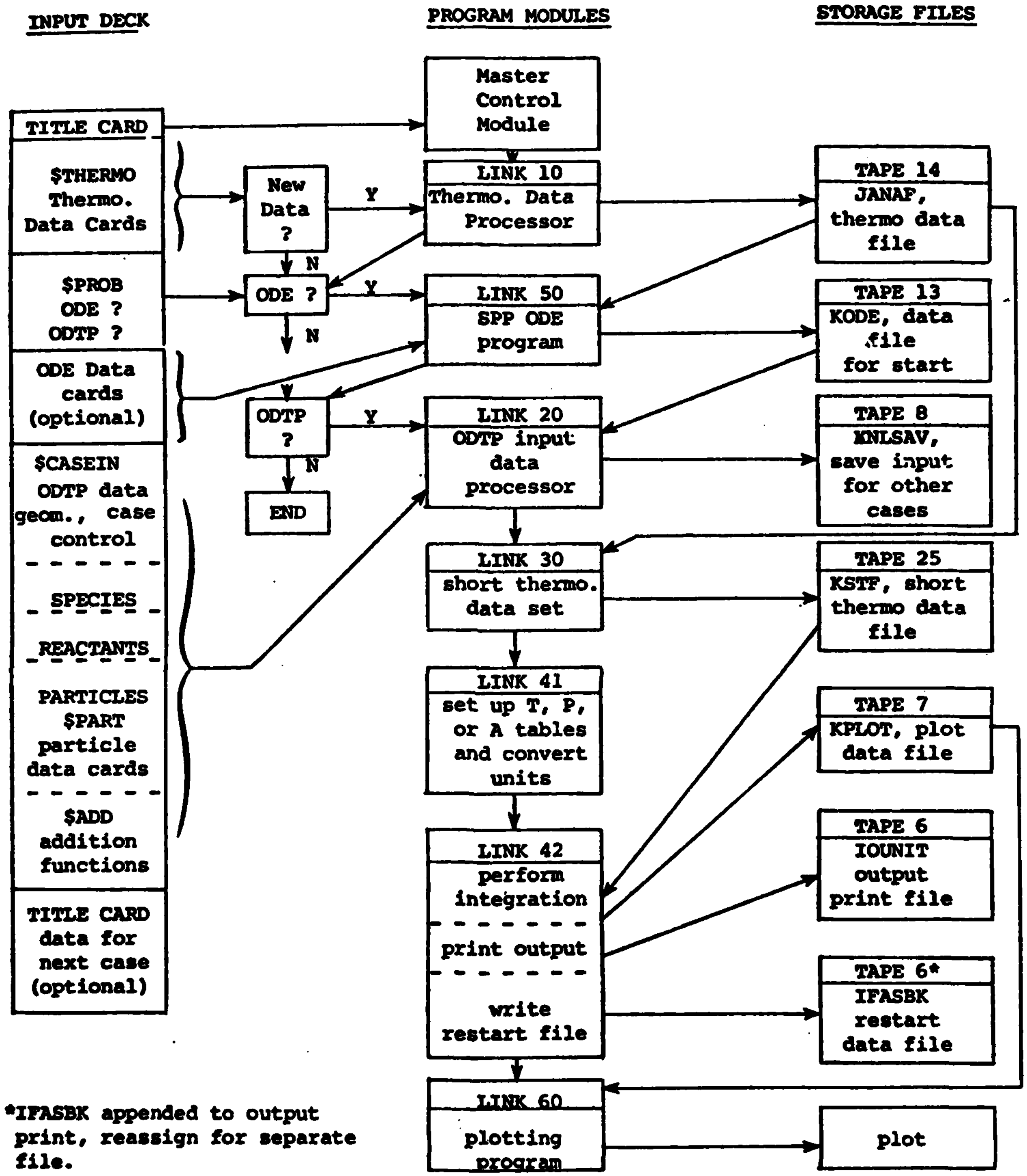
AD-A089 831 JOHNS HOPKINS UNIV LAUREL MD CHEMICAL PROPULSION INF--ETC F/G 21/8.2
JANNAF PERFORMANCE STANDARDIZATION SUBCOMMITTEE, 13TH MEETING M--ETC(U)
JUL 80 H F HEGE N00024-78-C-5384
UNCLASSIFIED CPIA-PUB-321 NL

2 of 4
AD
A089831





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



*IFASBK appended to output print, reassign for separate file.

Figure 1. OD3P program structure showing relationship between input deck, program modules and data storage files.

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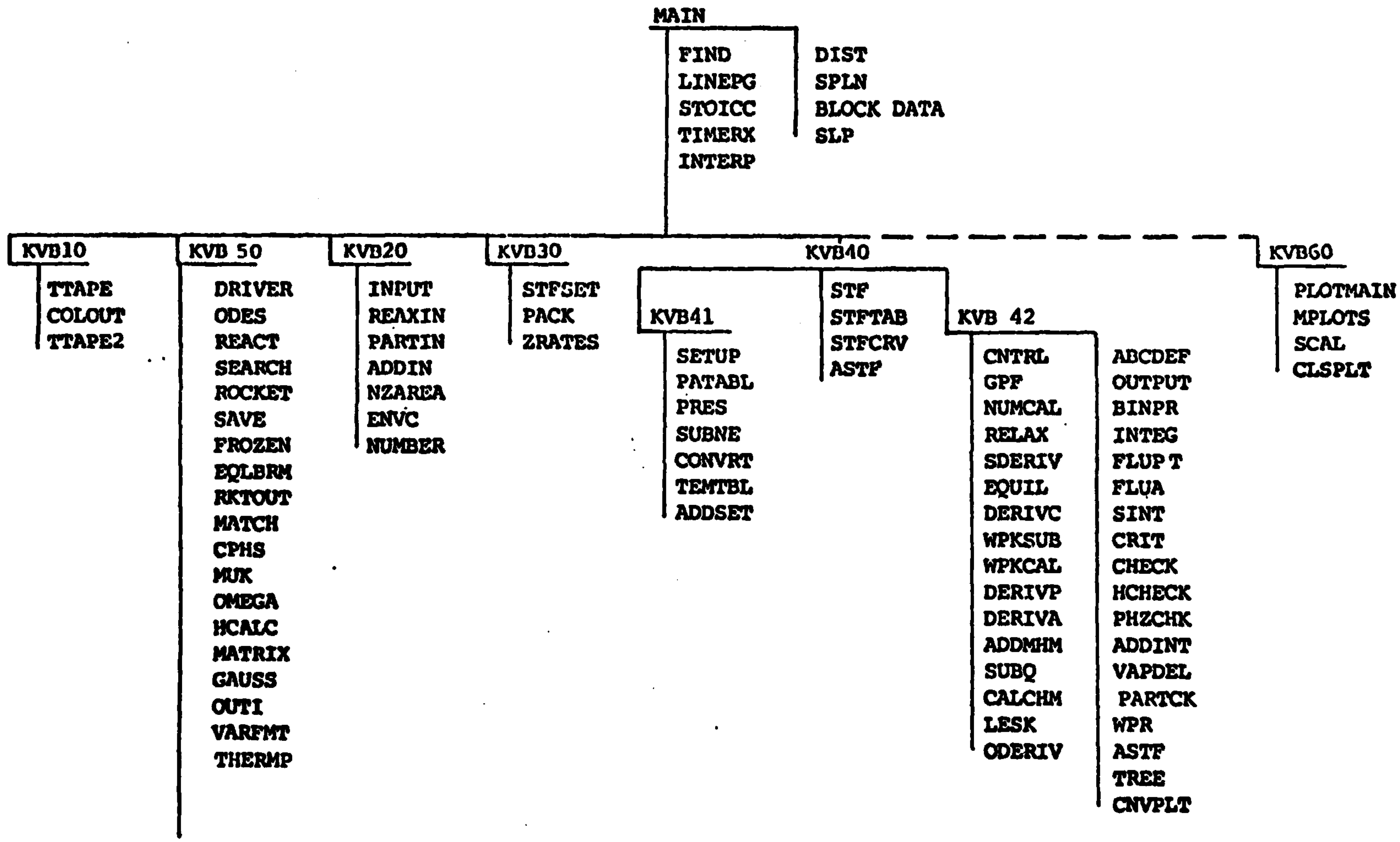

Figure 2. OD3P overlay structure.

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TABLE 1

INPUT DECK STRUCTURE AND FILE USEAGE

Input Deck Structure Summary

Input to OD3P is divided into the following sections:

1. TITLE CARD - the contents of this card will appear at the top of each print station output.
2. $THERMØ - namelist input controlling input of new thermodynamic data or the use of a previously generated thermodynamic data file.
3. THERMODYNAMIC DATA - includes gaseous species data and particle species data in either JANNAF table form or curve fits.
4. $PROB - namelist for specifying operation of the ODE link for starting conditions and the ODTP link for the three-phase flow calculation.
5. REACTANTS - ODE reactant cards per NASA SP-273
   OMIT - omit species for ODE
   INSERT - insert species for ODE
   NAMELISTS
   $ODE - namelist input for ODE per NASA SP-273 (Ref. 1)
   as modified by SPP (Ref. 2)
6. $CASEIN - namelist data which defines ODTP initial conditions, the type of calculation requested, and other specific case input.
7. SPECIES CARDS - data set containing the gaseous species to be considered (in ODTP) and their initial concentrations (if not input from ODE).
8. REACTION CARDS - data set containing the reaction set for the gaseous species, and any third body reaction rate ratios to be specified.
9. PARTICLES CARDS - when particles are to be considered this data set specifies their species and initial V_{pk}, ρ_{pk}, T_{pk}, r_{pk}, and m_{pk} (note: ρ_{pk} = lbm of particle per ft^3 of control volume, m_{pk} = bulk density = lbm of particle per ft^3 of particle). Note optional input in $PART for ODE start.
10. $PART - when particles are to be considered this namelist input defines the particle size change parameters specified for the particles.
11. $ADD - when mass, energy, or momentum addition for gas or particles is specified this namelist input defines the schedules for the addition rates.
12. $DATA - data set for output plotting.

Table 2 shows the input deck structure.

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TABLE 2

OD3P INPUT DATA SET DESCRIPTION

Data Set	Card Column Number 1 2 3 4 5 6 7 8 9	Section Explaining Data Set	Notes
Title card		3.1	1
First card	80 columns free field title		
Last card	None, only 1 title card allowed		
Thermo Namelist		3.2	1
First card	$THERMO		
Last card	$END		
CurveFit Data		3.3	2
First card	THERMO		
Last card	END		
First card	LOW T CPHS — optional		
Last card	END LOW T CPHS — optional		
Tabular Data		3.3	2
First card	First master gas specie card		
Last card	Last particle H or F card		
Problem Card		3.4	1
First card	$PROB		
Last card	$END		
ODE Reactants		3.5.1	3
First card	REACTANTS		
Last card	Blank Card Required		
ODE Omit & Insert		3.5.2	
First card	OMIT		
Last card	None Required		
First card	INSERT		
Last card	None Required		
ODE Namelist		3.5.3	3
First card	NAMELISTS		
Second card	$ODE		
Last card	$END		
ODTP Case Data		3.6	4
First card	$CASEIN		
Last card	$END		
Species cards		3.7	4
First card	$SPECIES		
Last card	None, Reactions Must Follow		
Reactions		3.8	6
First card	REACTIONS		
Last card	LAST REAX		
Third Body Ratios		3.8	6
First card	THIRD BODY		
Last card	LAST CARD		
Particle cards		3.9	6
First card	PARTICLES		
Last card	None Required		
Particle Namelist		3.10	6
First card	$PART		
Last card	$END		
Addition Functions		3.11	6
First card	$ADD		
Last card	$END		
Plotting Data		3.12	5
First card	$DATA		
Last card	$END		

Notes:
1. Mandatory
2. Optional, not required if data exists, select either curve or table data.
3. Required if ODE option selected.
4. Required if ODTP option selected.
5. Required if data plotting selected.
6. Optional.

TABLE 3

PRINT STATION OUTPUT DATA

<u>Gas Properties</u>

Velocity	ft/sec	
Temperature	°R	
Heat Capacity	BTU/lbm-°R	
Gas Viscosity	lbm/ft-sec	
Density	lbm/ft^3	
Molecular Wt	lbm/lbmole (of gas only)	
γ	unitless	
Prandtl Number	unitless	
Compling Term A	1/Unit Length	See Analysis for definition of the coupling terms.
Compling Term B	1/Unit Length	
Compling Term C	lbm/(ft-sec^2-Unit Length)	
Compling Term E	1/Unit Length	
Mach Number	unitless	
Pressure	PSIA	
Area	ft^2	
Axial Position	Unit Length	
Time	seconds	
Iterations	unitless	
Delivered Thrust Coefficient	unitless	Downstream of Throat only
Delivered Spec. Impulse	sec	
Vacuum Thrust Coefficient	unitless	
Vacuum Spec. Impulse	sec	
C*, Characteristic Velocity	ft/sec	

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TABLE 3 (contd)

Species Concentration	Mass Fraction
Gass Mass Flux	lb/sec
Particle Mass Flux	lb/sec
Total Mass Flux	lb/sec
Cumul. Mass Flux Error	lb/sec
Cumul. Mass Flux Error	percent
Gas Energy Flux	Btu/sec
Particle Energy Flux	Btu/sec
Total Energy Flux	Btu/sec
Cumul. Energy Flux Error	Btu/sec
Cumul. Energy Flux Error	percent
Gas Momentum Flux	ft - lbm/sec^2
Particle Momen. Flux	ft - lbm/sec^2
Total Momen. Flux	ft - lbm/sec^2
Cumul. Momen. Flux Error	ft - lbm/sec^2
Cumul. Momen. Flux Error	percent
Current Step Size	unit length
P used/P = RO.R.T	unitless
Gas H $(H + V^2/2)$	Btu/lbm
Molecular Weight	lb mixture/mole gas
Molecular Weight	lb mixture/mole mixture
Integrated Gas Mass Added	lbm/sec
Integrated Part. Mass Added	lbm/sec
Integ. Energy Added	Btu/sec

TABLE 3 (contd)

Wall Radiation Flux	Btu/s/ft^2 wall
Wall Temperature	°R
Integ. Momentum Added	ft/sec
1 - Σc_i, Species Summation	mass fraction
Percent dT/T per step	°R/°R per step
Energy Error per step as dT/T	percent per step
Maximum Species dc_i/c_i	percent per step
A.dx	unitless
B.dx	unitless
Gas Equivalence Ratio	unitless
Integ. Particle Mass Transfer	lb/s/ft^3 gas
Mean Diameter, all particles	micrometers
Geometric Standard Deviation, all groups	unitless
Mean Diameter, each set	micrometers
Geometric Standard Deviation, each set	unitless

TABLE 3 (contd)

Particle Properties (Printed for each Group)

Particle Phase	
Radius	ft., microns
Phase Volume Fraction	unitless
Velocity	ft/sec
Density	lbm/ft^3 volume of gas
Temperature	°R
Bulk Density	lbm/ft^3 particle
W_p^e, W_p^i, W_p^c, W_p^k	lbm/(ft^3 sec)
Number Density	Particles/ft^3
Compling Term D	l/unit length
Compling Term F	l/unit length
Reynolds Number	unitless
Nussult Number	unitless
Knudsen Number	unitless
Weber Number	unitless
Drag Coefficient	unitless
Velocity Relaxation	(sec-Unit L)/ft
Temperature Relaxation	(sec-Unit L)/ft
$\rho_{pk} \cdot V_{pk} \cdot A$	lbm/sec
Particle Mass Flux Error Term	lbm/sec
Integrated Particle Vaporization	lbm

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PARTICLE BREAKUP AND COLLISIONS

Particle breakup calculations using the Extended Delta SPP test case were performed starting with 30 µm and 300 µm median particle sizes. Nine groups were used with an initial geometric standard deviation of 1.9. Table 4 shows that for both calculations the particles broke up to nearly the same mean diameter. Of interest is that the larger initial sizing (300 µm) produced a slightly smaller final diameter. The breakup ratio used was 2 to 1, that is, at any point where a particle Weber number exceeds the critical value of $4/C_D$, the particle diameter is reduced by a factor of 2. Figure 3 shows the size distributions for the initial 30 µm median size case and at the throat for that case. The throat distribution remains approximately log-normal as expected but the geometric standard deviation is much lower. There is also a shift in the size arrangement of the groups. Groups 1, 5, and 9 remain respectively the smallest, median and largest size but other groups shift around. The geometric standard deviation of 1.9 for the initial particle sizing is actually based on measurements at the nozzle exit. It would appear that a larger value should be used at the nozle inlet so that the exit distributions would be closer to 1.9.

Figure 4 taken from NASA SP8039, shows particle size correlations for solid rocket motors. The Extended Delta test case mean particle sizes agree well with the NASA SP8039 curve but is higher than the SPP correlation (which is currently being revised).

Particle size as a function of axial position, plotted by OD3P, is shown in Figure 5 for an initial D_{43} of 30 µm with nine particle groups and a geometric standard deviation forsize distribution of 1.9. The position X = 0 is the throat.

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TABLE 4. EXTENDED DELTA TEST CASE PARTICLE BREAKUP AND COLLISIONS

	Case 1	Case 2
Initial median diam, µm	30	300
Initial mean diam, D_{43}, µm	36	360
Initial geom. std dev.	1.9	1.9
Throat mean diam, D_{43}, µm	8.45	7.51
Throat geom. std dev.	1.26	1.232
Exit mean diam, D_{43}, µm	8.34	7.14
Exit geom. std dev.	1.32	1.288

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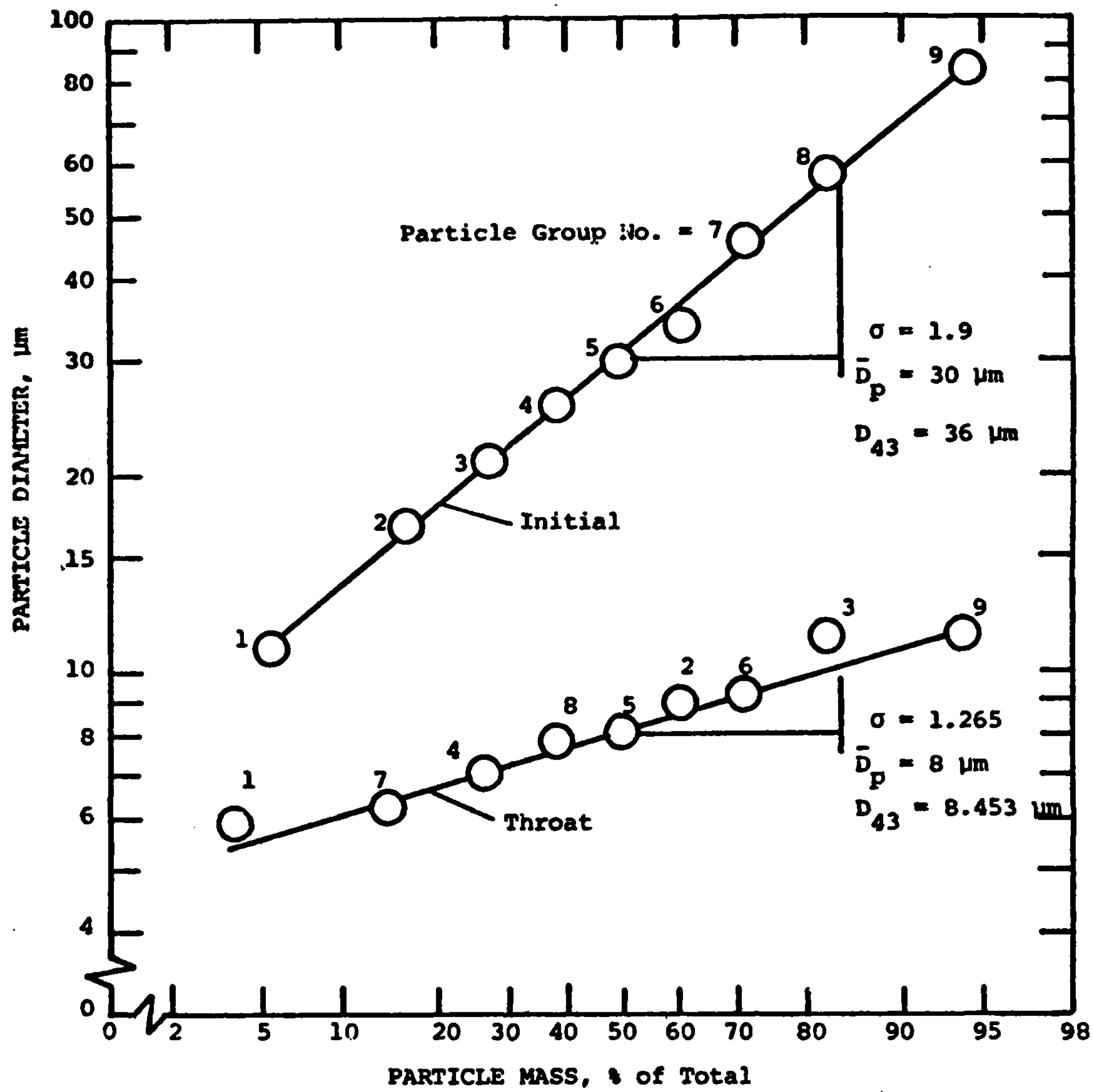

Figure 3. $Al_2O_3(L)$ particle size distribution with particle breakup and collisions.

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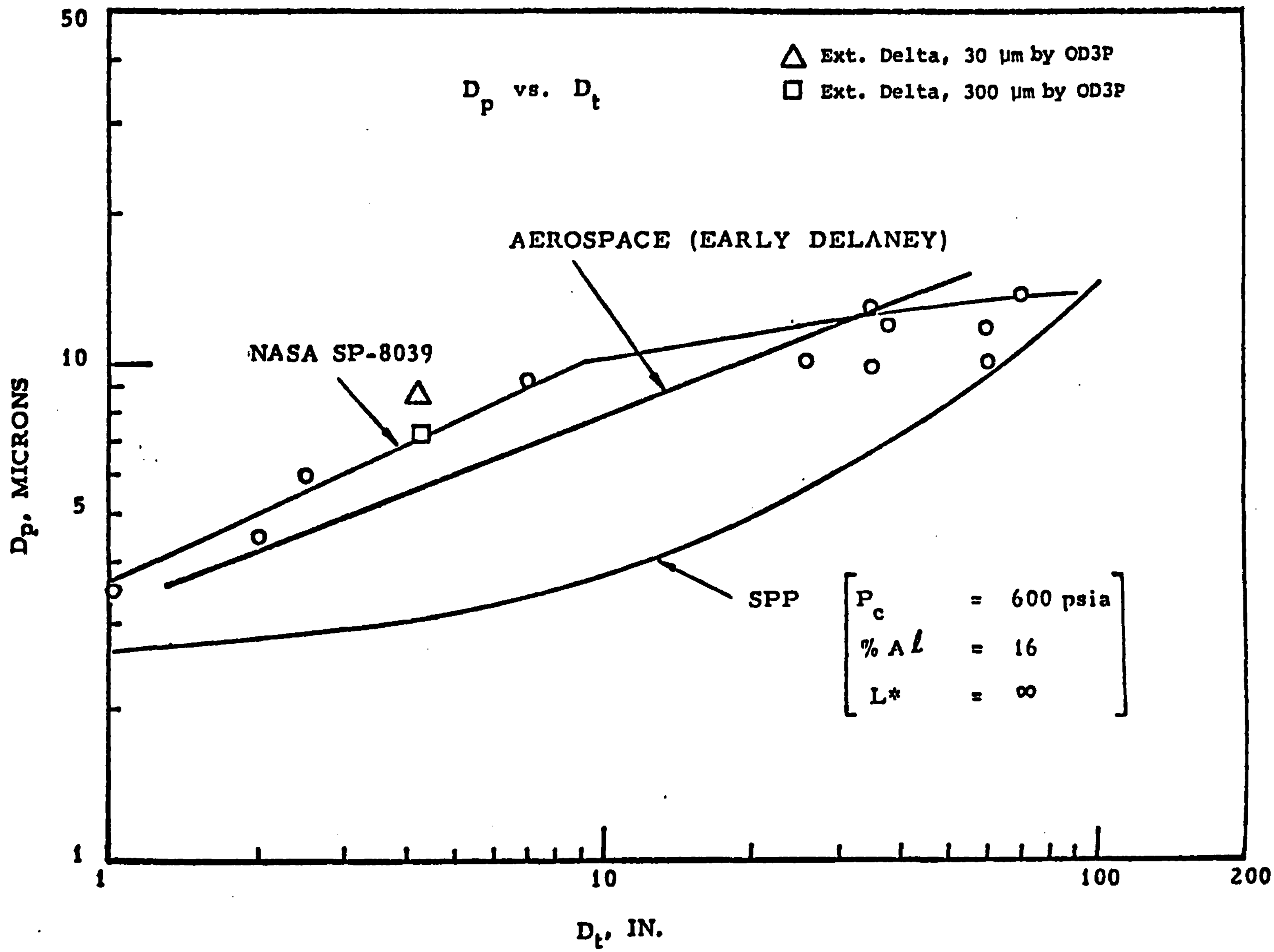

Figure 4. Particle size comparison for breakup calculation.

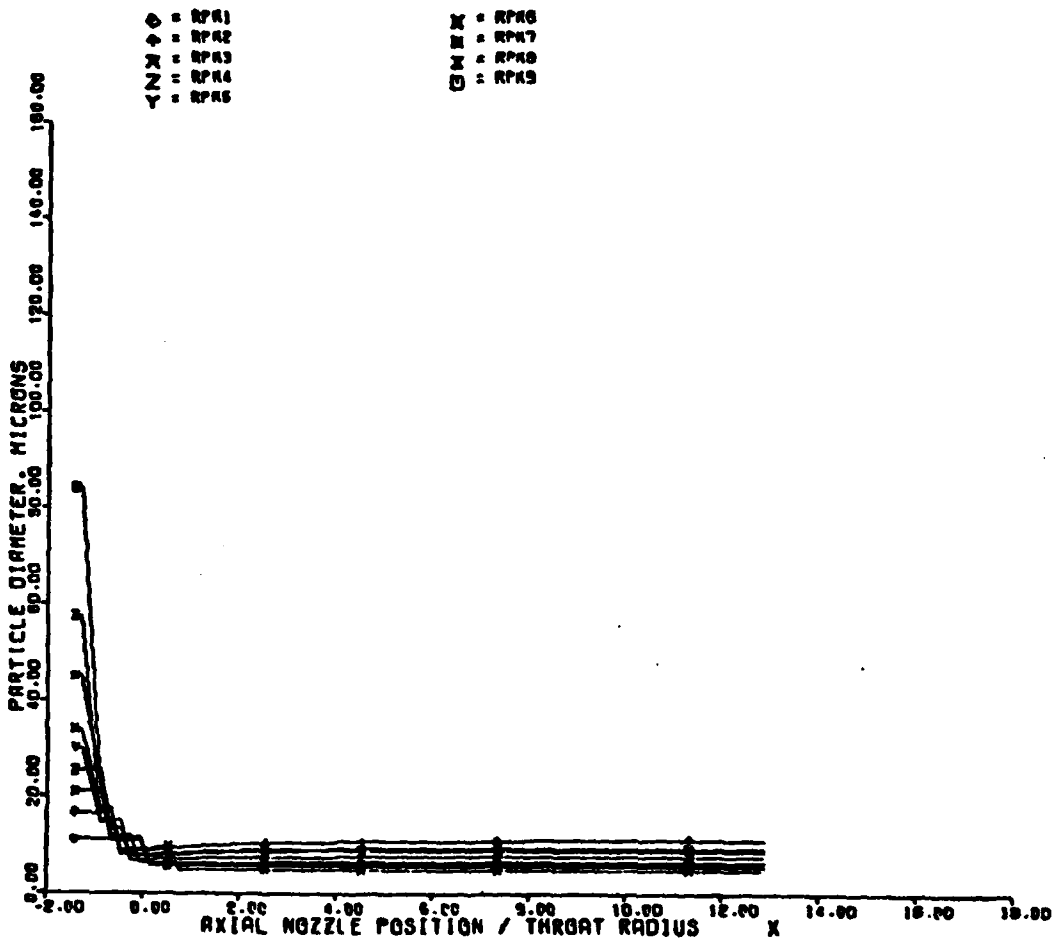

Figure 5. Extended Delta, nine particle groups, breakup, collisions.

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All nine groups break up before or at the throat; some groups break up more than once. Particle size of the larger particles beyond the throat grows slightly due to collisions. Collision rate is low because the particles are all nearly the same size.

SPECIES AND KINETIC REACTIONS

KVB developed a species and kinetic reaction set for a typical fluorinated propellant containing 23 gaseous species and 76 reactions. This set was presented at the 12th JANNAF PSS meeting in Salt Lake.[1] Since that meeting the set of 76 reactions has been updated, as shown in Table 5, to include the most recent kinetic rate data.

In using this set it is important to understand the assumptions on which it is based. The reaction set was developed for a specific set of species as shown in Table 5. Species are shown in four groups. The first group are those that are important to the energy release during nozzle expansion of a non-fluorinated propellant. These species are listed in order of decreasing magnitude of energy release. The second group shows additional major and minor species for fluorinated propellants. The third group includes species that are moderately high in concentration (>0.0001 mole fraction) but do not contribute significantly to energy release. The fourth group contains three species which are not important to energy release but are important to consider for performance based on restricted equilibrium. This is due to the fact that for full equilibrium $AlCl_3$ does not form during expansion; rather it disappears. However, when Al_2O_3 formation is suppressed as in restricted equilibrium, fairly large amounts of $AlCl_3$ are formed.

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[1] Cherry, S., "Kinetic Rate Data Screening and Update Procedure," 12th Meeting Minutes of the JANNAF Performance Standardization Subcommittee, Salt Lake City, Utah, January 25-26, 1979.

In developing the set of 76 reactions, the following 23 species were used: 15 species from the first group (excluding Al_2O_3 and N_2), the five major fluorine species from the second group, and N and AlOH from the third group. The latter two were included to provide a kinetic path for NO. Selection of these species was based on ODE calculations only with fluorinated propellants. Therefore, the use of a subset of the 76 reaction set for non-fluorinated propellants requires further consideration. At the 12th PSS meeting, Steve Cherry of KVB presented a preliminary screened set of 16 reactions involving 18 gaseous species, excluding fluorinated species. This set was based on previous screening of an original Al set included in the SPP initial version. A further subset of fifteen reactions (excluding $CO + O = O_2$) with 18 species was screened using updated rates from the final KVB set by Software Engineering Associates in the SPP program.[2] These results indicated a change in restricted equilibrium I_{sp} of only 0.08% compared with the full set of reactions shown in Table 5 (excluding fluorinated species and including four reactions involving Cl_2, $AlCL_2$, and $AlCl_3$). This SEA set of 15 reactions is therefore considered appropriate for use with non-fluorinated propellants when performing restricted equilibrium calculations. The fact that this set allows $AlCl_3$ to increase during expansion requires further assessment when the restriction on mass transfer is removed as in OD3P. KVB plans further work, starting from the SEA/KVB set of 15 reactions and excluding the reactions involving Cl_2, $AlCl_2$, and $AlCl_3$.

[2] Nickerson, G. R., Coats, D. E. and Hersen, R. W., "Solid Rocket Motor Performance Predictions Using the Improved SPP Computer Model," 16th JANNAF Combustion Meeting, Monterey, California, September 10-14, 1979.

TABLE 5. REACTION SET FOR ALUMINIZED PROPELLANTS WITH N-F BINDERS

REACTIONS					
N+N=N2,	A=1.E18,	N=1.,	B=0.0,	CHERRY(1967)	001
H+H=H2,	A=1.09E18,	N=1.,	B=0.0,	JENSEN/JONES(1978)	002
H+CL=HCL,	A=1.45E22,	N=2.,	B=0.0,	JENSEN/JONES(1978)	003
ALOF=ALF+O,	A=4.5E10,	N=-0.5,	B=130.0,	BAHN(1974)	004
O+H=OH,	A=3.62E18,	N=1.,	B=0.0,	JENSEN/JONES(1978)	005
OH+H=H2O,	A=3.22E22,	N=2.,	B=0.0,	JENSEN/JONES(1978)	006
ALCLF=ALF+CL,	A=4.5E10,	N=-0.5,	B=81.2,	BAHN(1974)	007
ALCL=AL+CL,	A=1.6E12,	N=-0.5,	B=113.3,	BAHN(1974)	008
N+O=NO,	A=6.4E16,	N=0.5,	B=0.0,	BAULCH(1973)	009
ALO=AL+O,	A=1.7E12,	N=-0.5,	B=113.3,	BAHN(1974)	010
ALO+OH=ALO2H,	A=3.0E16,	N=0.5,	B=0.0,	ESTIMATE	011
ALOCL=ALO+CL,	A=4.6E10,	N=-0.5,	B=124.3,	BAHN(1974)	012
ALOCL=ALCL+O,	A=4.6E10,	N=-0.5,	B=124.3,	BAHN(1974)	013
CO+O=CO2,	A=2.54E15,	N=0.0,	B=4.37,	JENSEN/JONES(1978)	014
ALO+H=ALOH,	A=3.0E16,	N=0.5,	B=0.0,	ESTIMATE	015
AL+OH=ALOH,	A=3.0E16,	N=0.5,	B=0.0,	ESTIMATE	016
END TBR REAX					
CL+H2=HCL+H,	A=8.43E12,	N=0.0,	B=4.233,	JENSEN/JONES(1978)	017
H2+O=OH+H,	A=1.80E10,	N=-1.0,	B=8.903,	JENSEN/JONES(1978)	018
H2+OH=H2O+H,	A=1.14E9,	N=-1.3,	B=3.627,	JENSEN/JONES(1978)	019
CO+OH=CO2+H,	A=1.69E7,	N=-1.3,	B=-0.656,	JENSEN/JONES(1978)	020
CL+OH=HCL+O,	A=2.41E12,	N=0.0,	B=4.968,	JENSEN/JONES(1978)	021
HCL+OH=H2O+CL,	A=1.30E13,	N=0.0,	B=2.087,	JENSEN/JONES(1978)	022
OH+OH=O+H2O,	A=6.30E12,	N=0.0,	B=1.093,	JENSEN/JONES(1978)	023
CO2+H2=CO+H2O,	A=9.5E8,	N=-0.5,	B=15.,	TUNDER(1967)	024
N+OH=NO+H,	A=5.3E11,	N=-0.5,	B=5.628,	CHERRY(1967)	025
N2+O=NO+N,	A=7.60E13,	N=0.0,	B=75.516,	JENSEN/JONES(1978)	026
CO2+N=CO+NO,	A=1.05E11,	N=-0.5,	B=59.62,	CHERRY(1967)	027
AL+OH=ALO+H,	A=5.E11,	N=-0.5,	B=5.619,	ESTIMATE	028
ALO+CO=AL+CO2,	A=1.E11,	N=-0.5,	B=6.466,	ESTIMATE	029
AL+HCL=ALCL+H,	A=5.E11,	N=-0.5,	B=5.673,	ESTIMATE	030
ALO+CL=ALCL+O,	A=5.E11,	N=-0.5,	B=6.466,	ESTIMATE	031
ALCL+CO2=ALOCL+CO,	A=1.E11,	N=-0.5,	B=6.995,	ESTIMATE	032
ALO+HCL=ALOCL+H,	A=1.E11,	N=-0.5,	B=5.673,	ESTIMATE	033
ALCL+OH=ALOCL+H,	A=1.E11,	N=-0.5,	B=5.619,	ESTIMATE	034
HF+AL=ALF+H,	A=5.E11,	N=-0.5,	B=7.486,	ESTIMATE	035
ALF2+H=ALF+HF,	A=5.E11,	N=-0.5,	B=7.175,	ESTIMATE	036
ALCLF+H=ALF+HCL,	A=5.E11,	N=-0.5,	B=4.707,	ESTIMATE	037
ALCLF+H=HF+ALCL,	A=5.E11,	N=-0.5,	B=6.961,	ESTIMATE	038

(continued)

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TABLE 5 (Continued).

```
ALCLF+O=ALOF+CL,          A=5.E11,    N=-0.5,  B=4.707,   ESTIMATE     039
OH+ALOCL=CL+ALO2H,        A=1.E11,    N=-0.5,  B=7.270,   ESTIMATE     040
N+ALO=NO+AL,              A=5.E11,    N=-0.5,  B=6.466,   ESTIMATE     041
ALO+ALCL=AL+ALOCL,        A=1.E11,    N=-0.5,  B=6.513,   ESTIMATE     042
CO2+ALF=CO+ALOF,          A=1.E11,    N=-0.5,  B=6.995,   ESTIMATE     043
ALF+HCL=HF+ALCL,          A=1.E10,    N=-0.5,  B=73.755,  ESTIMATE     044
HF+ALO=ALOF+H,            A=1.E11,    N=-0.5,  B=7.486,   ESTIMATE     045
HF+ALO=ALF+OH,            A=1.E10,    N=-0.5,  B=71.025,  ESTIMATE     046
ALF2+HCL=HF+ALCLF,        A=1.E10,    N=-0.5,  B=65.411,  ESTIMATE     047
HF+ALOCL=ALOF+HCL,        A=1.E10,    N=-0.5,  B=75.121,  ESTIMATE     048
ALO+HCL=OH+ALCL,          A=1.E10,    N=-0.5,  B=61.799,  ESTIMATE     049
AL+ALF2=ALF+ALF,          A=5.E11,    N=-0.5,  B=7.175,   ESTIMATE     050
ALF+OH=ALOF+H,            A=1.E11,    N=-0.5,  B=5.619,   ESTIMATE     051
ALCLF+AL=ALF+ALCL,        A=5.E11,    N=-0.5,  B=6.961,   ESTIMATE     052
ALF+ALO=ALOF+AL,          A=1.E11,    N=-0.5,  B=7.640,   ESTIMATE     053
ALF2+ALO=ALF+ALOF,        A=1.E11,    N=-0.5,  B=7.175,   ESTIMATE     054
ALF+ALCLF=ALCL+ALF2,      A=1.E11,    N=-0.5,  B=6.961,   ESTIMATE     055
ALCLF+ALO=ALF+ALOCL,      A=1.E11,    N=-0.5,  B=4.707,   ESTIMATE     056
ALF+ALOCL=ALCL+ALOF,      A=1.E11,    N=-0.5,  B=7.175,   ESTIMATE     057
ALOCL+N=ALCL+NO,          A=5.E11,    N=-0.5,  B=7.175,   ESTIMATE     058
ALCLF+ALO=ALCL+ALOF,      A=1.E11,    N=-0.5,  B=6.961,   ESTIMATE     059
ALO+H2O=ALO2H+H,          A=1.E11,    N=-0.5,  B=6.566,   ESTIMATE     060
ALO+N=NO+AL,              A=5.E11,    N=-0.5,  B=6.466,   ESTIMATE     061
ALF2+ALOCL=ALCLF+ALOF,    A=1.E10,    N=-0.5,  B=73.058,  ESTIMATE     062
ALOF+N=ALF+NO,            A=5.E11,    N=-0.5,  B=7.500,   ESTIMATE     063
ALO+HCL=ALOH+CL,          A=1.E11,    N=-0.5,  B=5.673,   ESTIMATE     064
ALCL+OH=ALOH+CL,          A=1.E11,    N=-0.5,  B=6.561,   ESTIMATE     065
ALOH+OH=H+ALO2H,          A=1.E11,    N=-0.5,  B=5.627,   ESTIMATE     066
AL+H2O=ALOH+H,            A=5.E11,    N=-0.5,  B=6.566,   ESTIMATE     067
ALO+H2=ALOH+H,            A=1.E11,    N=-0.5,  B=5.731,   ESTIMATE     068
ALO+OH=ALOH+O,            A=1.E11,    N=-0.5,  B=5.627,   ESTIMATE     069
ALOH+HF=ALOF+H2,          A=1.E10,    N=-0.5,  B=70.336,  ESTIMATE     070
ALOH+HF=ALF+H2O,          A=1.E10,    N=-0.5,  B=74.645,  ESTIMATE     071
ALOH+HCL=ALOCL+H2,        A=1.E10,    N=-0.5,  B=61.110,  ESTIMATE     072
ALOH+HCL=ALCL+H2O,        A=1.E10,    N=-0.5,  B=65.419,  ESTIMATE     073
ALF+ALO2H=ALOH+ALOF,      A=1.E10,    N=-0.5,  B=83.930,  ESTIMATE     074
ALOH+H2O=ALO2H+H2,        A=1.E10,    N=-0.5,  B=65.657,  ESTIMATE     075
ALO2H+ALCL=ALOH+ALOCL,    A=1.E10,    N=-0.5,  B=72.458,  ESTIMATE     076
LAST REAX
THIRD BODY REAX RATE RATIOS
ALL EQUAL 1.0
LAST CARD
```

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TABLE 6. SPECIES CONSIDERED IMPORTANT FOR ROCKET MOTOR PERFORMANCE ANALYSIS

I. MAJOR SPECIES BASED ON ENERGY RELEASE (NON-FLUORINATED)

Al_2O_3	HCl	O	AlOCl
CO	OH	AlCl	CO_2
N_2	H_2O	NO	
H	Cl	AlO	
H_2	Al	AlO_2H	

II. ADDITIONAL SPECIES IMPORTANT FOR FLUORINATED PROPELLANTS

Major	Minor
HF	$AlClF_2$
AlF_2	F
AlOF	$AlCl_2F$
AlF	AlF_3
AlClF	

III. SPECIES HIGH IN CONCENTRATION BUT NOT IMPORTANT TO ENERGY RELEASE

AlH	O_2
$AlCl_2$	N
Al_2O	AlOH

IV. SPECIES IMPORTANT IN RESTRICTED EQUILIBRIUM BUT NOT FOR FULL EQUILIBRIUM

$AlCl_3$	$AlCl_2$	Cl_2

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CONSTANT FRACTIONAL LAG PROCEDURE FOR DRIVING VARIABLE

One-dimensional kinetic calculations required specification of a defined independent variable, usually pressure in the subsonic and sonic regions and area in the supersonic region. The pressure function is generated using an average equilibrium pressure expansion coefficient from the chamber to the throat. This is an appropriate approximation for calculations with gas-particle velocity and temperature equilibrium. However, for the non-equilibrium procedure of OD3P, it was necessary to revise the calculation to include an approximation more appropriate for flow with particle velocity and temperature lags relative to the gas. The approximation used is the constant fractional lag procedure of Kliegel[3]. The procedure was developed, as shown in an appendix to this paper, for both pressure and temperature defined calculations. While the pressure defined mode is conventional, the temperature defined mode is novel and was developed to improve the numerical solution of gas-particle flows with kinetics. Solution of the gas-particle equations in OD3P involves up to 104 simultaneous equations for the gas species concentrations (40); gas velocity, density, area and pressure or temperature (4); and six equations for each of 10 particle groups (60). For near-equilibrium flow, numerical instability is a major difficulty in obtaining solutions because the species kinetic rates are such strong functions of temperature. The use of a temperature-defined mode for specifying the driving variable was found to minimize any tendency for numerical instability due to the stiff

[3] Kliegel, J. R., "Gas Particle Nozzle Flows," Ninth (International) Symposium on Combustion, The Combustion Institute, 1962.

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equation problem. This procedure is considered useful only for cases in which the gas mixture is in fact very near equilibrium and the effect on prediction of kinetic loss has not yet been evaluated in full gas-particle calculations. For cases where significant kinetic non-equilibrium exists, it is considered more appropriate to retain the pressure-defined mode.

ROCKET MOTOR VERIFICATION CASES

In order to assess the accuracy of OD3P and demonstrate its operation, a set of six motor test cases is being used. These cases are identical to those currently being used for the Improved SPP. Final execution of these cases is not yet completed pending accuracy verification of all the particle size change models in OD3P, together with kinetics and numerical integration methods. However, all cases have been run successfully through the ODE module and through the initial setup routines of OD3P, including generation of tables for either pressure or temperature defined independent variable. Table 7 presents the lag parameters that result from the independent variable generation. Particle-to-gas mass flow ratios ($\dot{w}_p/\dot{w}_g$) are similar for all the motors except RSM which is very low. The nozzle discharge coefficients are also similar for the first five cases but lower as expected for RSM. All the results shown were based on particle size using the Improved SPP particle size correlation. The particle size from that correlation is checked against a particle breakup criteria using a Weber number of 28. In all cases the particle size from the correlation was below the critical breakup size. The prediction of C_D needs to be further assessed based on actual OD3P particle calculations which are yet to be completed.

TABLE 7. CONSTANT FRACTIONAL LAG PARAMETERS

Motor	$\frac{\dot{w}_p}{\dot{w}_g}$	$\bar{\gamma}$	K*	L*	C_D
Extended delta	0.3979	1.1247	0.886	0.871	1.0150
Titan III C	0.4116	1.1288	0.843	0.767	1.0240
C4 Stage 3(ADP)	0.4669	1.1237	0.839	0.767	1.0276
IUS Large Motor	0.4708	1.1194	0.834	0.767	1.0274
AIM	0.4264	1.1255	0.835	0.753	1.0257
Reduced Smoke Maverick	0.004	1.1675	0.821	0.683	1.0031

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APPENDIX A

CONSTANT FRACTIONAL LAG METHOD FOR TEMPERATURE AND PRESSURE DEFINED SOLUTIONS

Obtain the following from equilibrium solution:

T_c, chamber temperature

T^*, throat temperature

h_c, chamber enthalpy

h^*, throat enthalpy

Calculate equilibrium expansion coefficient

$$\gamma_e = 2\frac{T_c}{T^*} - 1 \tag{C-1}$$

Calculate average specific heat

$$\bar{c}_p = \frac{\left|h_c - h^*\right|}{T_c - T^*} \tag{C-2}$$

Calculate average gas specific heat

$$\bar{c}_{pg} = \bar{c}_p\left(1 + \frac{\dot{w}_p}{\dot{w}_g}\right) - \frac{\dot{w}_p}{\dot{w}_g} \quad c_{pp} \tag{C-3}$$

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Calculate gas expansion coefficient

$$\gamma_g = \frac{\gamma_e}{1 + \left(\frac{\dot{w}_p}{\dot{w}_g}\right)^* \left(\frac{C_{pp}}{\bar{C}_{pg}}\right)^* (\gamma_e - 1)} \tag{C-4}$$

Calculate the two-phase flow expansion coefficient by iterating the following:

$$B = \frac{1 + \left(\dot{w}_p/\dot{w}_g\right)^* {K^*}^2}{1 + \left(\dot{w}_p/\dot{w}_g\right)^* \left(C_{pp}/\bar{C}_{pg}\right)^* L^*} \tag{C-5}$$

$$C = 1 + \left(\dot{w}_p/\dot{w}_g\right)^* \left\{K^* \left[\left(1-K^*\right)\gamma_g + K^*\right] + \left(\gamma_g - 1\right)\left(C_{pp}/\bar{C}_{pg}\right)^* B L^*\right\} \tag{C-6}$$

$$\bar{\gamma} = 1 + \left(\gamma_g - 1\right)\frac{B}{C} \tag{C-7}$$

In the above, assume the particle lags are zero to begin the iteration; i.e., $K^* = L^* = 1$

Estimate the two-phase flow throat conditions

$$T_g^* = \frac{2\, T_c}{\bar{\gamma} + 1} \tag{C-8}$$

$$V_g^* = \left(\frac{2\, \bar{C}_{pg}\, T_c}{B}\, \frac{\bar{\gamma} - 1}{\bar{\gamma} + 1}\right)^{1/2} \tag{C-9}$$

$$\rho_g^* = \rho_c \left(\frac{T_g^*}{T_c}\right)^{\frac{1}{\bar{\gamma} - 1}} \tag{C-10}$$

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For cases with no particles the above equations are sufficient and no iteration is necessary.

For flow with particles the following equations provide an estimate of the particle lags at the throat.

Calculate the mass average particle size for particles considered in the case

$$r_{43} = \frac{\sum_k r_{pk}\rho_{pk}/m_{pk}}{\sum_k \rho_{pk}/m_{pk}} \tag{C-11}$$

Calculate a maximum particle size based on particle break up

$$r_{crit}^{*} = \frac{g_c \, \sigma \, W_{e_{crit}}^{*}}{2\rho_g^{*} \, V_g^{*}(1-K^{*})} \tag{C-12}$$

Set r_p^* to the minimum of r_{43} and r_{crit}^*

Calculate C_D^*, f_p^*, μ^* and Pr^* by standard formulas.

Calculate particle density at the throat from:

$$T_p^{*} = T_c - L^{*}\left(T_c - T_g^{*}\right) \tag{C-13}$$

$$C_{pp} = f\left(T_p^{*}\right) \tag{C-14}$$

$$m_{pk}^{*} = m_{ri}\left[1 - a_i{'''}\left(T_p^{*} - T_{ri}\right)\right] \tag{C-15}$$

$$m_p^{*} = \frac{\sum_k m_{pk}^{*}\,\rho_{pk}}{\sum_k \rho_{pk}} \tag{C-16}$$

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Calculate the estimated particle lags.

$$D^* = \frac{\mu^* \, f_p^* \, r^*}{m_p^* \, r_p^* \, V_g^*} \tag{C-17}$$

$$K^* = \frac{V_p^*}{V_g^*} = \frac{9}{4} D^* \left[\frac{\bar{\gamma}+1}{2} \frac{R^*}{r^*}\right]^{1/2} \left\{\left[1 + \frac{8}{9D^*}\left(\frac{\bar{\gamma}+1}{2} \frac{R^*}{r^*}\right)^{-\frac{1}{2}}\right]^{1/2} - 1\right\} \tag{C-18}$$

$$L^* = \frac{T_c - T_p^*}{T_c - T_g^*} = \left[1 + 3 \, Pr^* \left(C_{pp}/\bar{C}_{pg}\right)^* \left(1-K^*\right)/K^*\right]^{-1} \tag{C-19}$$

Iterate the entire solution procedure above until K* and L* converge.

After convergence, calculate predicted nozzle mass flow

$$\dot{w}_T = \left[1 + \left(\dot{w}_p/\dot{w}_g\right)^*\right] \pi \, r^{*2} \, \rho_g^* \, V_g^* \tag{C-20}$$

Calculate the inlet contraction ratio

$$\frac{a_I}{a^*} \quad \frac{\dot{w}_T}{\rho_I \, V_I \, a^* \left(1 + \frac{\dot{w}_p}{\dot{w}_g}\right)_I} \tag{C-21}$$

Calculate a temperature table as a function of nozzle position with N values between the inlet and the throat.

$$\Delta T_{Table} = \frac{T_{gI} - T_g^*}{N} \qquad (C-22)$$

Calculate the area ratio for each table value of T_g

$$\frac{a}{a^*} = \left\{ \frac{\bar{\gamma}-1}{2} \frac{T_g}{T_c - T_g} \left[\frac{2}{\bar{\gamma}+1} \frac{T_c}{T_g} \right]^{\frac{\bar{\gamma}+1}{\bar{\gamma}-1}} \right\}^{1/2} \qquad (C-23)$$

Calculate a table of nozzle position from a/a* and the nozzle geometry. This produces a table of T_g and a versus x. The table of T_g and a versus x can be used in two ways during the temperature-defined solution at the two-phase flow:

1. Use $T_g = f(x)$, where x is the local position during solution.

2. Use $T_g = f(a)$, where a is the local calculated area.

The first method is the most stable because T_g will remain fixed at the forward point. However there will be a difference between calculated area and the tabular area. The throat may occur at a point that does not match the T_g^* calculated above.

The second procedure will tend to be less stable because the forward point temperature will change as a function of the calculated area. However, the calculated area may better match the geometric area.

The first method was selected for the program.

The above procedure is used to generate a temperature table for a temperature defined solution which is very stable for numerical integration when gas phase chemistry is near equilibrium and the gas species differential equations are very stiff.

The temperature defined procedure can be converted to pressure defined by the use of

$$\frac{P}{P_c} = \frac{T}{T_c}^{(\bar{\gamma}/\bar{\gamma}-1)} \qquad \text{(C-24)}$$

and

$$\frac{dP}{dx} = \frac{P_c}{T_c^{\bar{\gamma}/(\bar{\gamma}-1)}} \frac{\bar{\gamma}}{\bar{\gamma}-1} T^{1/(\bar{\gamma}-1)} \frac{dT}{dx} \qquad \text{(C-25)}$$

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JANNAF PERFORMANCE STANDARDIZATION SUBCOMMITTEE

FEBRUARY 14-15, 1980

SACRAMENTO, CALIFORNIA

ONE-DIMENSIONAL THREE PHASE FLOW REACTING GAS WITH MASS TRANSFER

EDWARDS AFB CONTRACT F04611-78-C-0011

KIM HUNTER

KVB, INC

TUSTIN, CALIFORNIA

KVB

A Research-Cottrell Company

2/14/80

KVB 11-23000

PARTICLE SIZE CHANGE MECHANISMS

VAPORIZATION	PARTICLE COLLISION
SUBLIMATION	DROPLET BREAK UP
MELTING	NUCLEATION
SOLIDIFICATION	CONDENSATION
GAS PHASE REACTIONS	RADIATION
HETEROGENEOUS REACTIONS	PARTICLE DENSITY VS. TEMP.

KVB 23000

OBJECTIVES

- IMPROVE PREDICTION OF EFFECT OF 2-PHASE LOSS ON PERFORMANCE OF SOLID PROPELLANT MOTORS
- DEVELOP ANALYTICAL METHODS FOR PARTICLE AND DROPLET SIZE CHANGE MECHANISMS
- INCORPORATE SIZE CHANGE MODELS INTO A COMPUTER PROGRAM WITH GAS-PARTICLE REACTION AND MASS TRANSFER
- VERIFY MODELS BY COMPARISON WITH TEST DATA

KVB 23000-2 2/78

TABLE 6. SPECIES CONSIDERED IMPORTANT FOR ROCKET MOTOR PERFORMANCE ANALYSIS

I. MAJOR SPECIES BASED ON ENERGY RELEASE (NON-FLUORINATED)

Al_2O_3	HCl	O	AlOCl
CO	OH	AlCl	CO_2
N_2	H_2O	NO	
H	Cl	AlO	
H_2	Al	AlO_2H	

II. ADDITIONAL SPECIES IMPORTANT FOR FLUORINATED PROPELLANTS

Major	Minor
HF	$AlClF_2$
AlF_2	F
AlOF	$AlCl_2F$
AlF	AlF_3
AlClF	

III. SPECIES HIGH IN CONCENTRATION BUT NOT IMPORTANT TO ENERGY RELEASE

AlH	O_2
$AlCl_2$	N
Al_2O	$AlOH$

IV. SPECIES IMPORTANT IN RESTRICTED EQUILIBRIUM BUT NOT FOR FULL EQUILIBRIUM

$AlCl_3$	$AlCl_2$	Cl_2

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TABLE 7. REACTION RATING FOR NON-FLUORINATED PROPELLANT (AT THROAT)

	REACTION	$X_j \cdot \Delta H_{298_j}$	$\left\lvert \dfrac{X_j \cdot \Delta H_{298_j}}{-7089} \right\rvert$
1.	$H + OH + M \rightarrow H_2O + M$	-7089	1.000
2.	$H_2 + OH \leftarrow H + H_2O$	+4416	0.623
3.	$H_2 + M \leftarrow H + H + M$	-3402	0.480
4.	$CO + OH \leftarrow CO_2 + H$	+1562	0.220
5.	$CO + O + M \rightarrow CO_2 + M$	-1090	0.154
6.	$HCl + M \leftarrow H + Cl + M$	-630	0.089
7.	$HCl + OH \leftarrow H_2O + Cl$	+465	0.066
8.	$AlCl_2 + H \rightarrow AlCl + HCl$	-338	0.048
9.	$Cl_2 + H \rightarrow HCl + Cl$	-227	0.032
10.	$Al + HCl \leftarrow AlCl + H$	+158	0.022
11.	$AlCl + OH \leftarrow AlOCl + H$	+135	0.019
12.	$AlCl + Cl + M \rightarrow AlCl_2 + M$	-87	0.012
13.	$AlO + HCl \leftarrow AlOCl + H$	+74	0.011
14.	$AlOH + OH \rightarrow H + AlO_2H$	-71	0.010
15.	$AlCl_2 + Cl + M \rightarrow AlCl_3 + M$	-49	0.007
16.	$CO + O \rightarrow CO_2$	-38	0.005

$\sum_{j=1}^{73} (X_j \cdot \Delta H_{298_j}) = -6256$, $\sum_{j=1}^{16} (X_j \cdot \Delta H_{298_j}) = -6209\ (0.993)$; $\sum_{j=1}^{11} (X_j \cdot \Delta H_{298_j}) = -6040\ (0.965)$

PARTICLE DENSITY EQUATION

$$\frac{d}{dx}\left(\rho_{pk} V_{pk} a\right) = -\left(w_{pk} + w_{pk}^{c}\right) r^{*} a + \left(\dot{S}_{pk} + \dot{S}_{pk}^{c}\right)\left(\rho V a\right)_{o}$$

FINITE DIFFERENCE FORM

$$\rho_{pk_2} = \rho_{pk_1}\left(\frac{P_2}{P_1}\right)^{\frac{1}{2}\left(\frac{M_2^2 - 1}{\gamma_2 M_2^2} + \frac{M_1^2 - 1}{\gamma_1 M_1^2}\right)} \exp\left[-D_{k_1}\left(x_2 - x_1\right)\right]$$

CONSERVATION FORM

$$\rho_{pk_2} = \frac{\left(\rho_{pk} V_{pk} a\right)_{o} - \int\left(w_{pk} + w_{pk}^{c}\right) r^{*} a \, dx + \int\left(\dot{S}_{pk} + \dot{S}_{pk}^{c}\right)\left(\rho V a\right)_{o} dx}{V_{pk_2} a_2}$$

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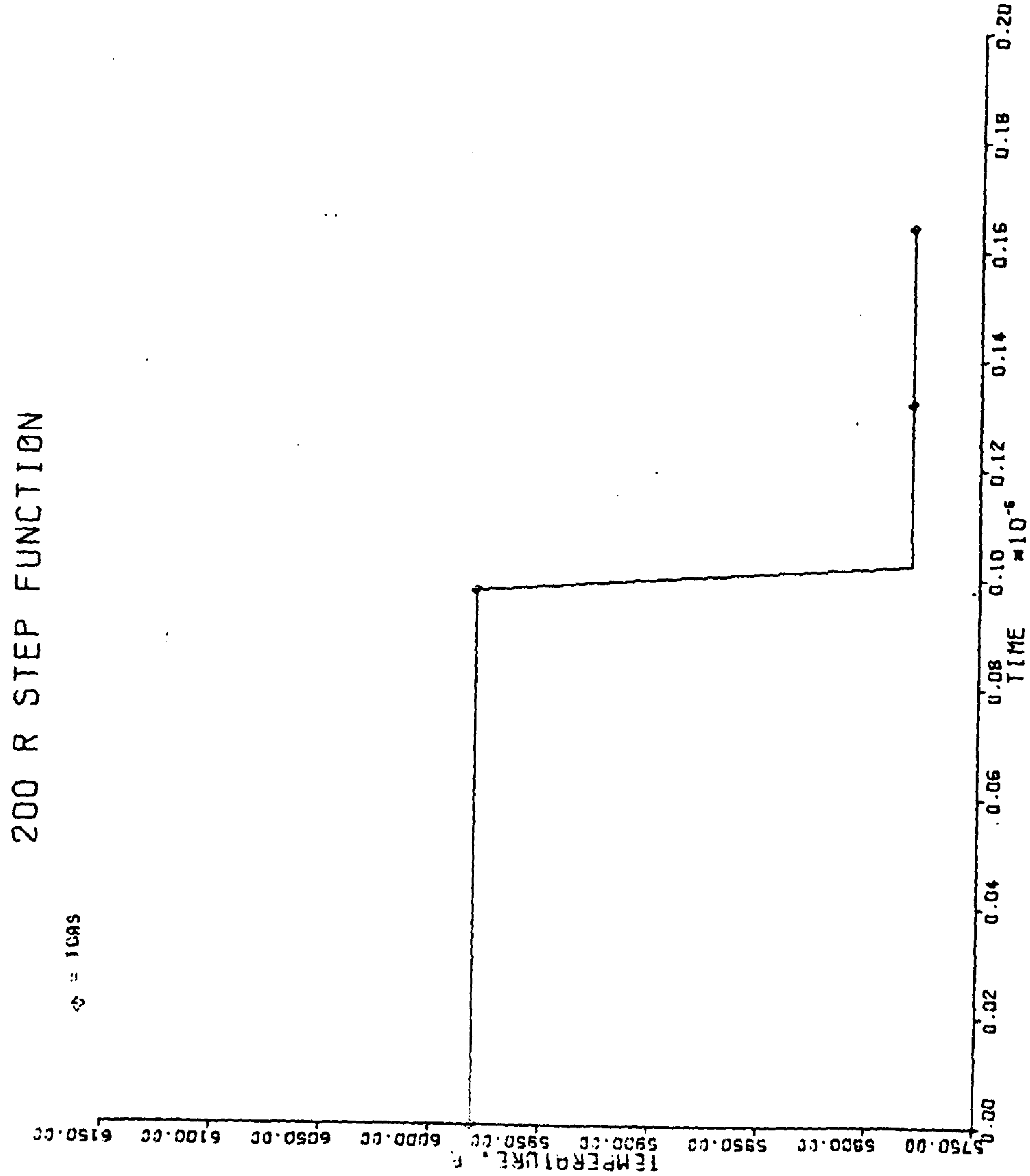
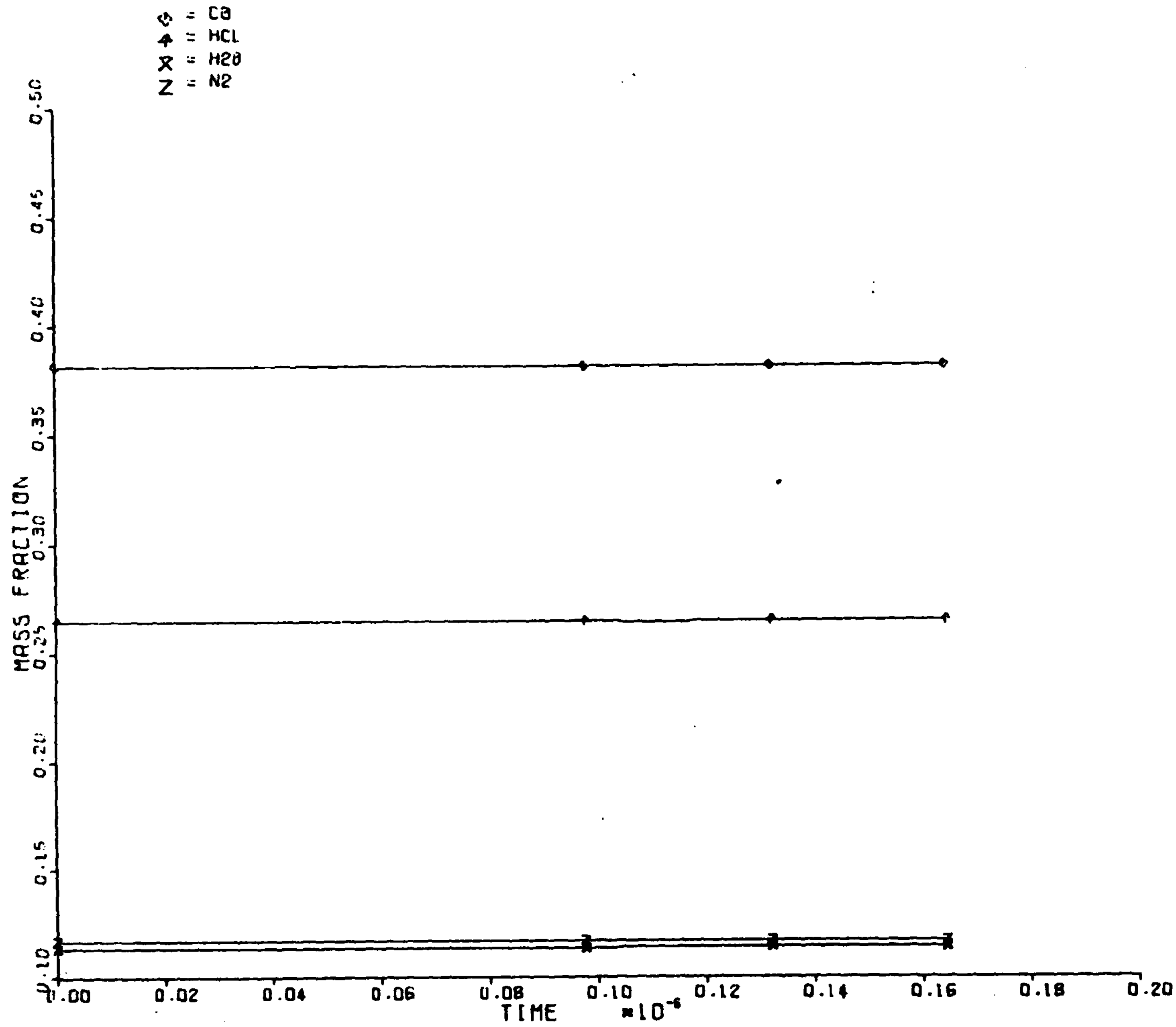
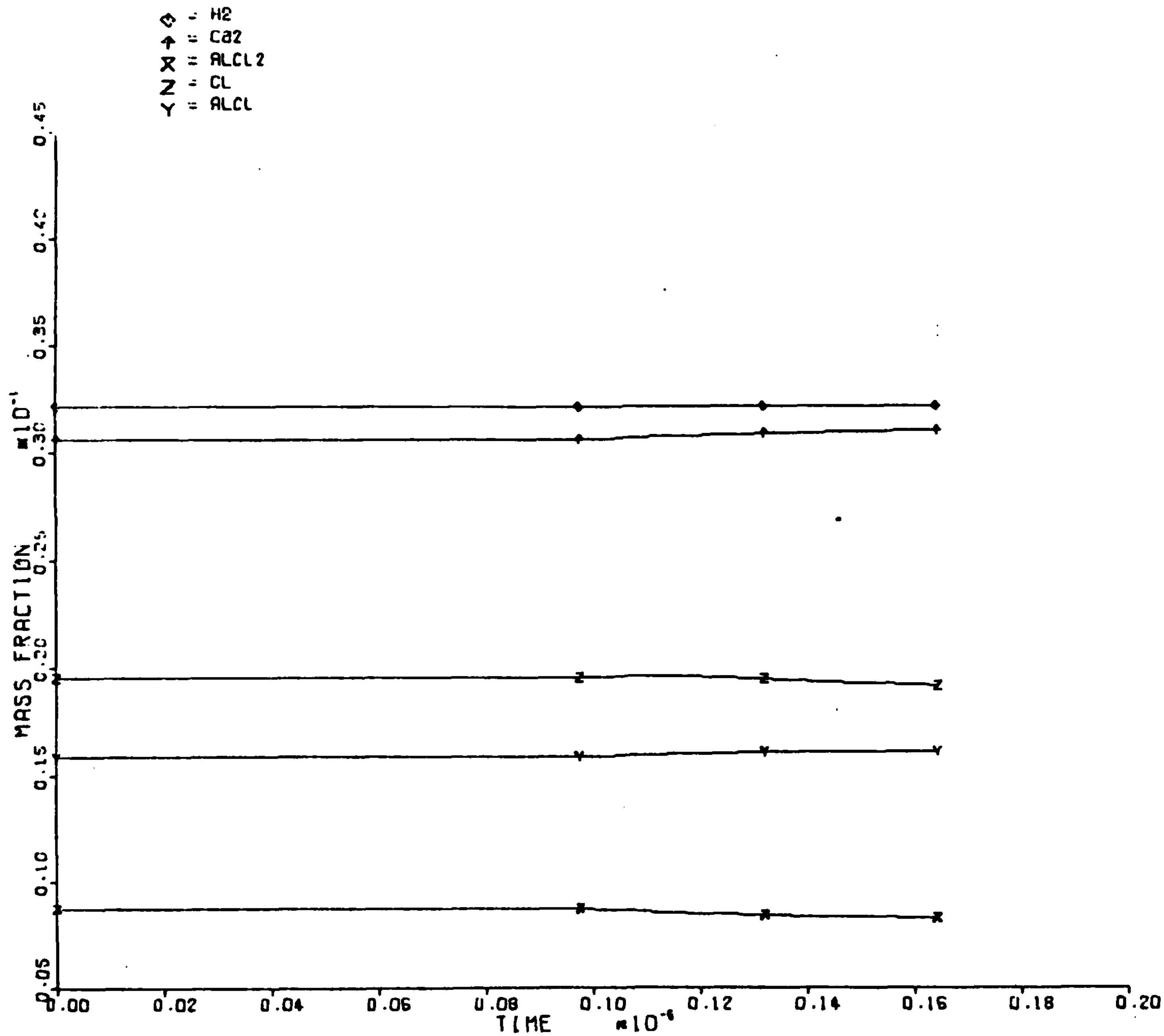


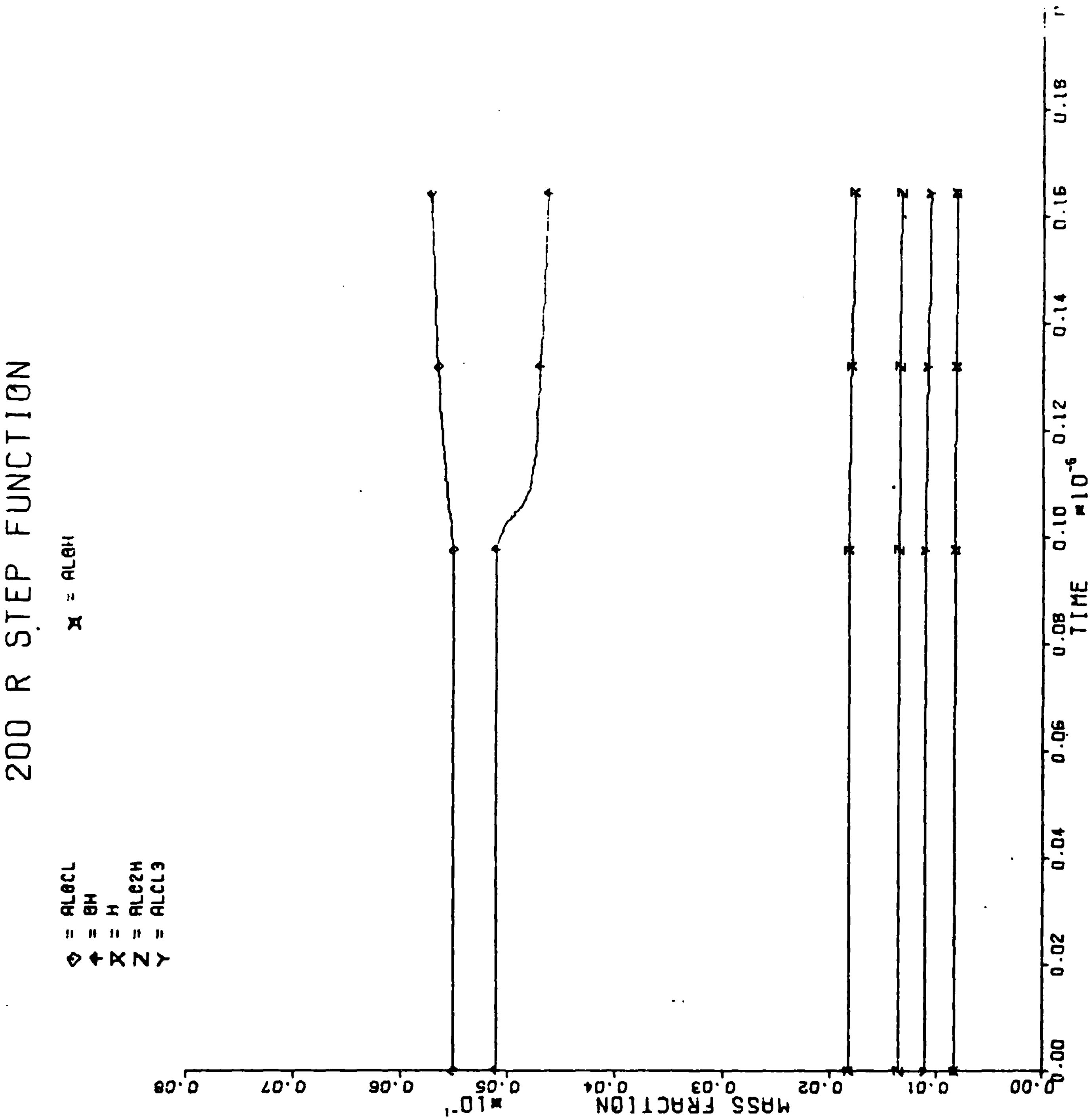
200 R STEP FUNCTION
◇ = 1GAS
TIME ×10⁻⁶
TEMPERATURE, R
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
5750.00
5800.00
5850.00
5900.00
5950.00
6000.00
6050.00
6100.00
6150.00

200 R STEP FUNCTION

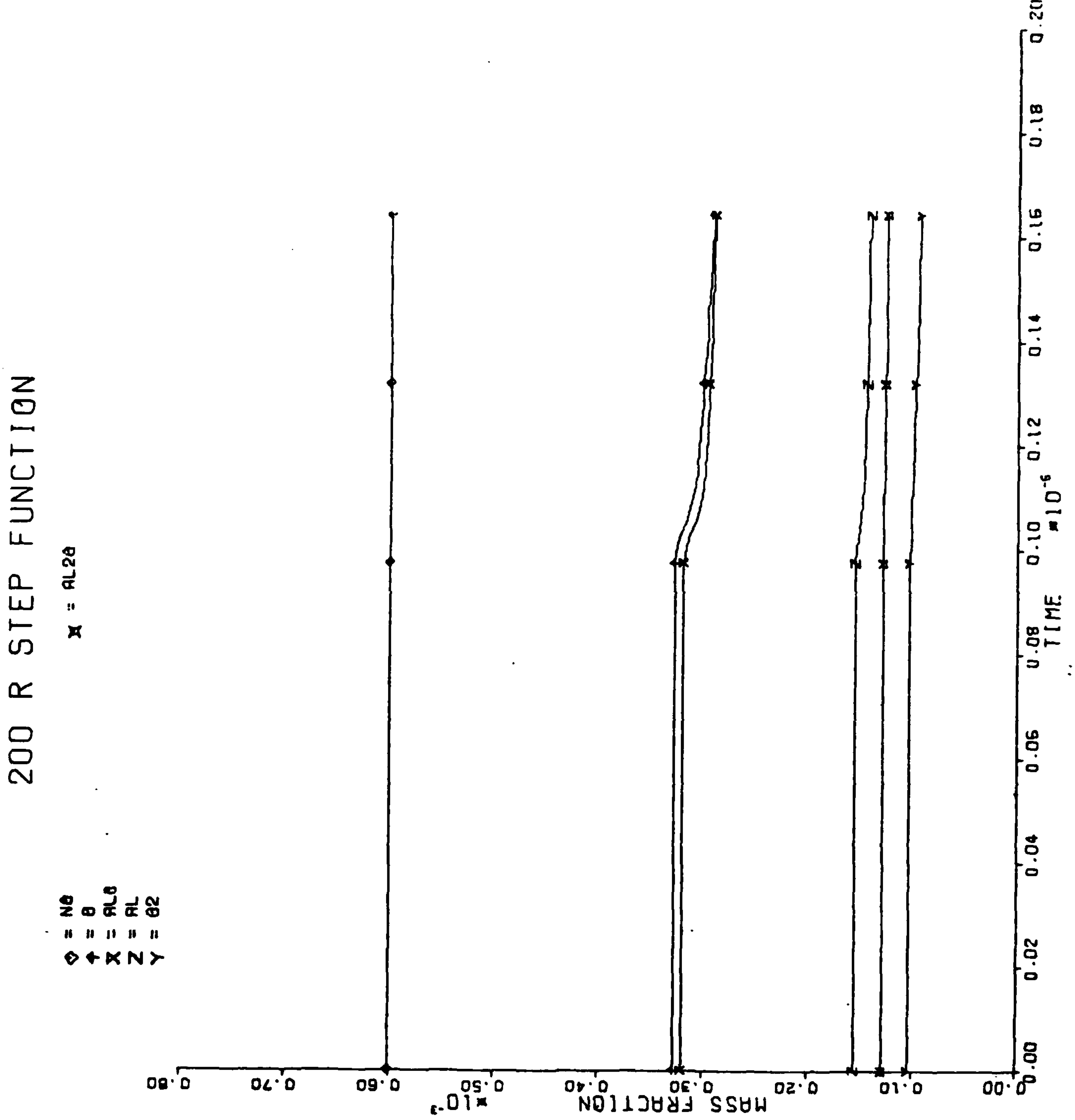


200 R STEP FUNCTION

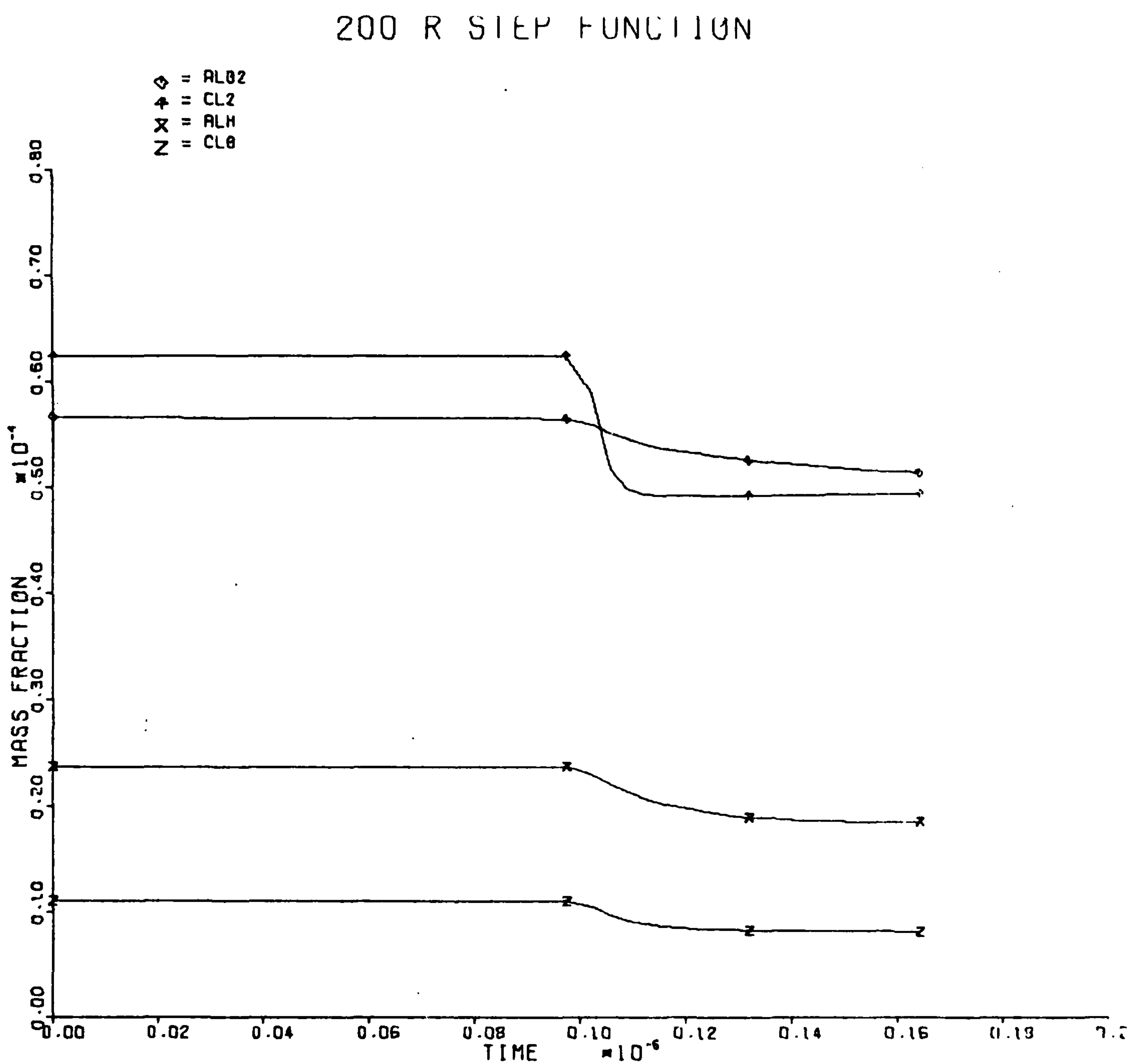


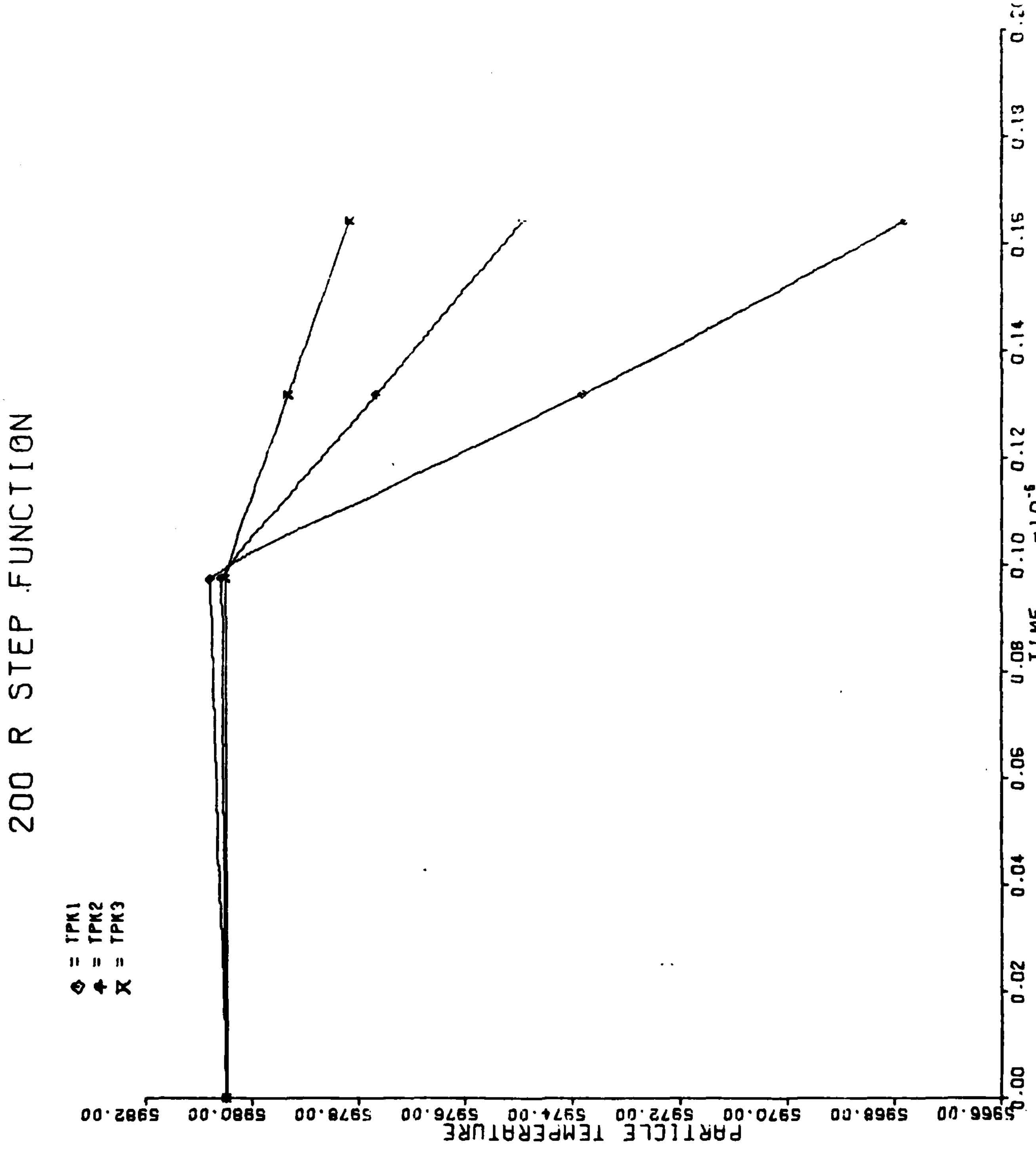


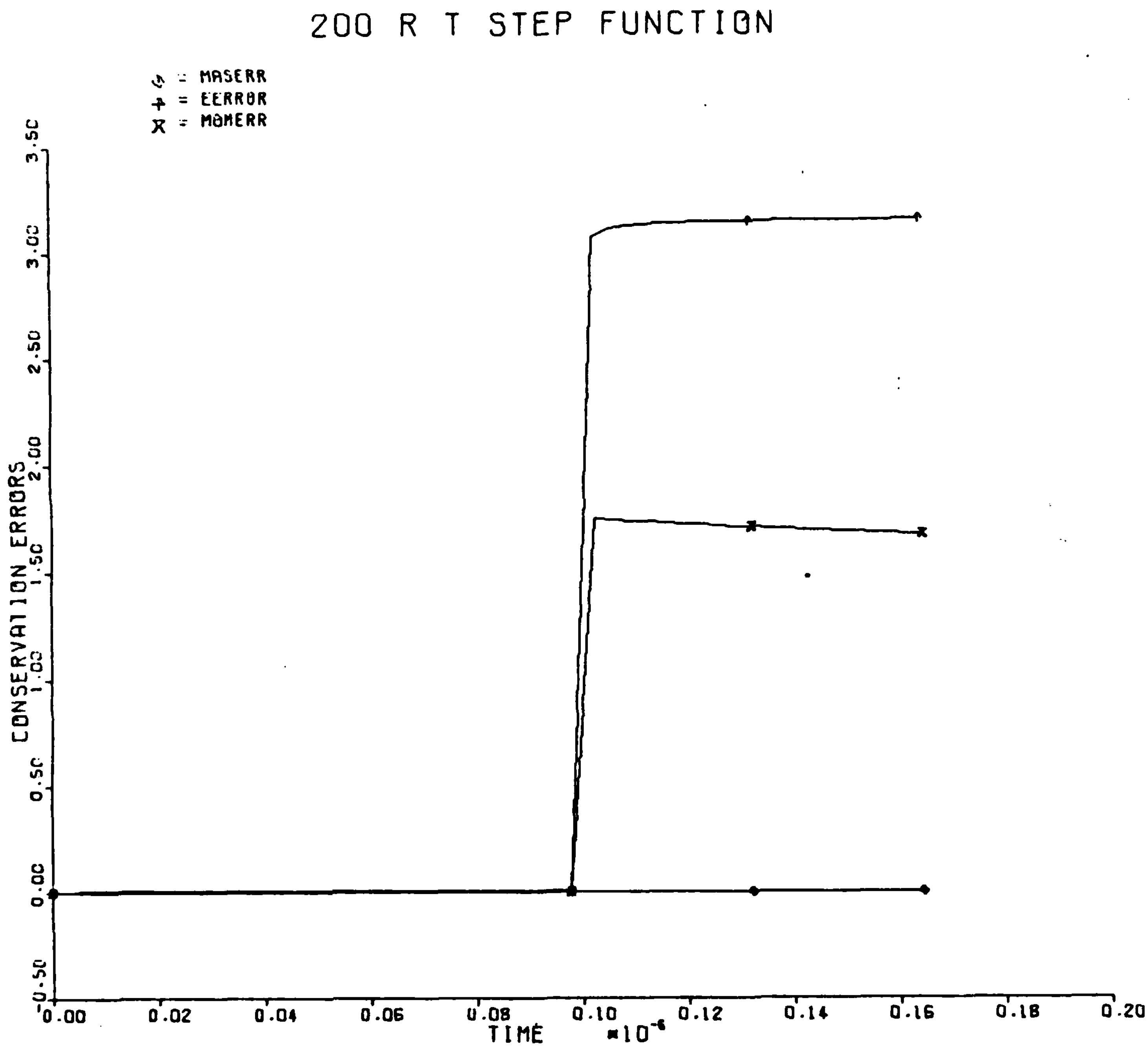
200 R STEP FUNCTION
♢ = ALBCL
✦ = BH
X = H
Z = ALC2H
Y = ALCL3
X = ALBH
MASS FRACTION
*10⁻¹
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
TIME *10⁻⁶
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18



200 R STEP FUNCTION
⌘ = AL2O
◇ = NO
✚ = O
X = ALO
Z = AL
Y = O2
MASS FRACTION
*10^-3
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
TIME *10^-6
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20


200 R STEP FUNCTION
◇ = ALO2
✚ = CL2
X = ALH
Z = CL8
MASS FRACTION
*10^-1
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
TIME *10^-6


200 R STEP FUNCTION
◇ = TPK1
+ = TPK2
X = TPK3
TIME $\times 10^{-6}$
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
PARTICLE TEMPERATURE
5966.00
5968.00
5970.00
5972.00
5974.00
5976.00
5978.00
5980.00
5982.00

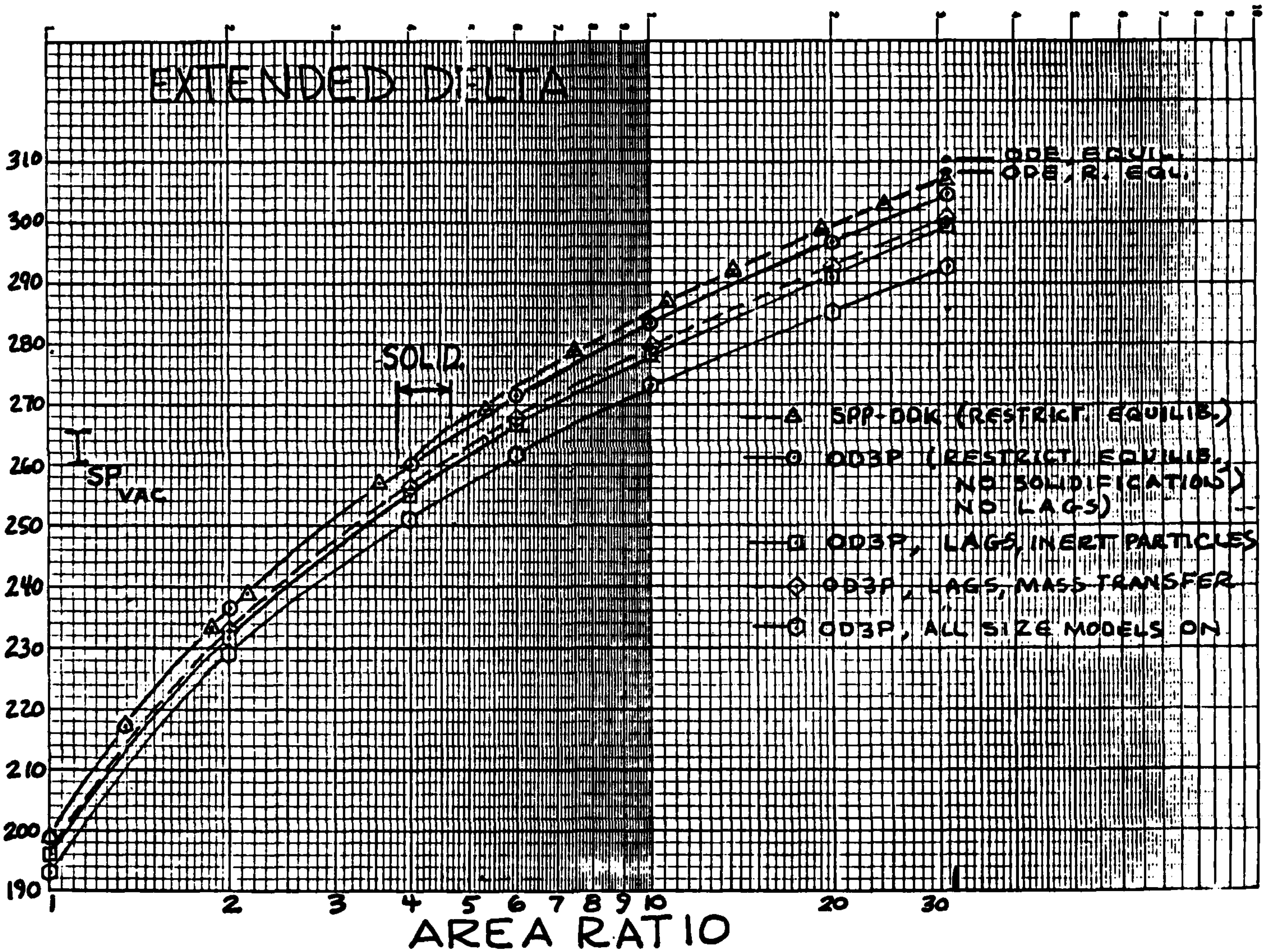

200 R T STEP FUNCTION
= MASERR
+ = EERROR
X = MOMERR
CONSERVATION ERRORS
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
TIME
*10^-6

OD3P - SPP COMPARISON

EXTENDED DELTA TEST CASE

73 REACTIONS - RESTRICTED EQUILIBRIUM

	ODE			SPP-ODK	OD3P				
	EQUIL.	RESTR. EQUIL.	FROZEN		FROZEN	TEMP. DEFINED	PRESS. DEF. THREE STEP SIZES		
THROAT	199.1	198.7	197.4	198.57	197.4	198.72	198.70	198.70	198.71
AR=4	261.7	260.6	256.6	260.2	256.6	260.21	260.15	260.16	260.25
AR=30.84	310.3	308.6	298.3	307.07	298.4	304.22	-	304.18	304.34
Avg. Step Size	-	-	-	0.005	.06	0.012	0.008	0.02	0.03
Run Time, Min.	-	-	-	25	0.77	11.4	12.3	6.9	4.2
Max Error, %	-	-	-	-	0.11	0.6	0.5	0.6	1.2



EXTENDED DELTA
$I_{SP_{VAC}}$
SOLID
ODE, EQUIL.
ODE, R. EQL.
SPP-DDK (RESTRICT. EQUILIB.)
OD3P (RESTRICT. EQUILIB., NO SOLIDIFICATION, NO LAGS)
OD3P, LAGS, INERT PARTICLES
OD3P, LAGS, MASS TRANSFER
OD3P, ALL SIZE MODELS ON
310
300
290
280
270
260
250
240
230
220
210
200
190
1
2
3
4
5
6
7
8
9
10
20
30
AREA RATIO

EFFECT OF MASS TRANSFER ON PERFORMANCE

EXTENDED DELTA TEST CASE

	$I^*_{SP_{VAC}}$	$I_{SP_{VAC}}$ EXIT	EXIT LOSS, SEC	
ODE-EQUILIBRIUM	199.1	310.3	0	1.7 SEC
ODE-RESTRICTED EQUIL.	198.7	308.6	1.70	
OD3P-RESTRICTED EQUIL. (NO SOLIDIFICATION)	198.7	304.2	6.1	
OD3P-MASS TRANSFER ONLY	196.3	299.9	10.4	1 SEC
OD3P-INERT PARTICLES	196.1	298.9	11.4	
OD3P-ALL SIZE CHANGE	193.5	292.5	17.8	
SPP-ODK + TD2P	-	289.7	20.6	
MEASURED	-	285.7	24.6	

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CONSTANT FRACTIONAL LAG PARAMETERS

Motor	$\frac{\dot{w}_p}{\dot{w}_g}$	$\bar{\gamma}$	K*	L*	C_D
Extended delta	0.3979	1.1247	0.886	0.871	1.0150
Titan III C	0.4116	1.1288	0.843	0.767	1.0240
C4 Stage 3(ADP)	0.4669	1.1237	0.839	0.767	1.0276
IUS Large Motor	0.4708	1.1194	0.834	0.767	1.0274
AIM	0.4264	1.1255	0.835	0.753	1.0257
Reduced Smoke Maverick	0.004	1.1675	0.821	0.683	1.0031

OD3P RESULTS FOR EXTENDED DELTA

	D^*, µm	K*	L*
Inert particles	1.55	.962	.910
$D^*_{43}=3.341$	2.86	.911	.805
	5.33	.832	.657
Mass transfer only	1.58	.962	.879
$D^*_{43}=3.33$	2.88	.911	.773
	5.34	.833	.622
All size change	1.53	.960	.902
$D^*_{43}=6.26$µm	3.19	.895	.771
	7.03	.796	.564

KVB
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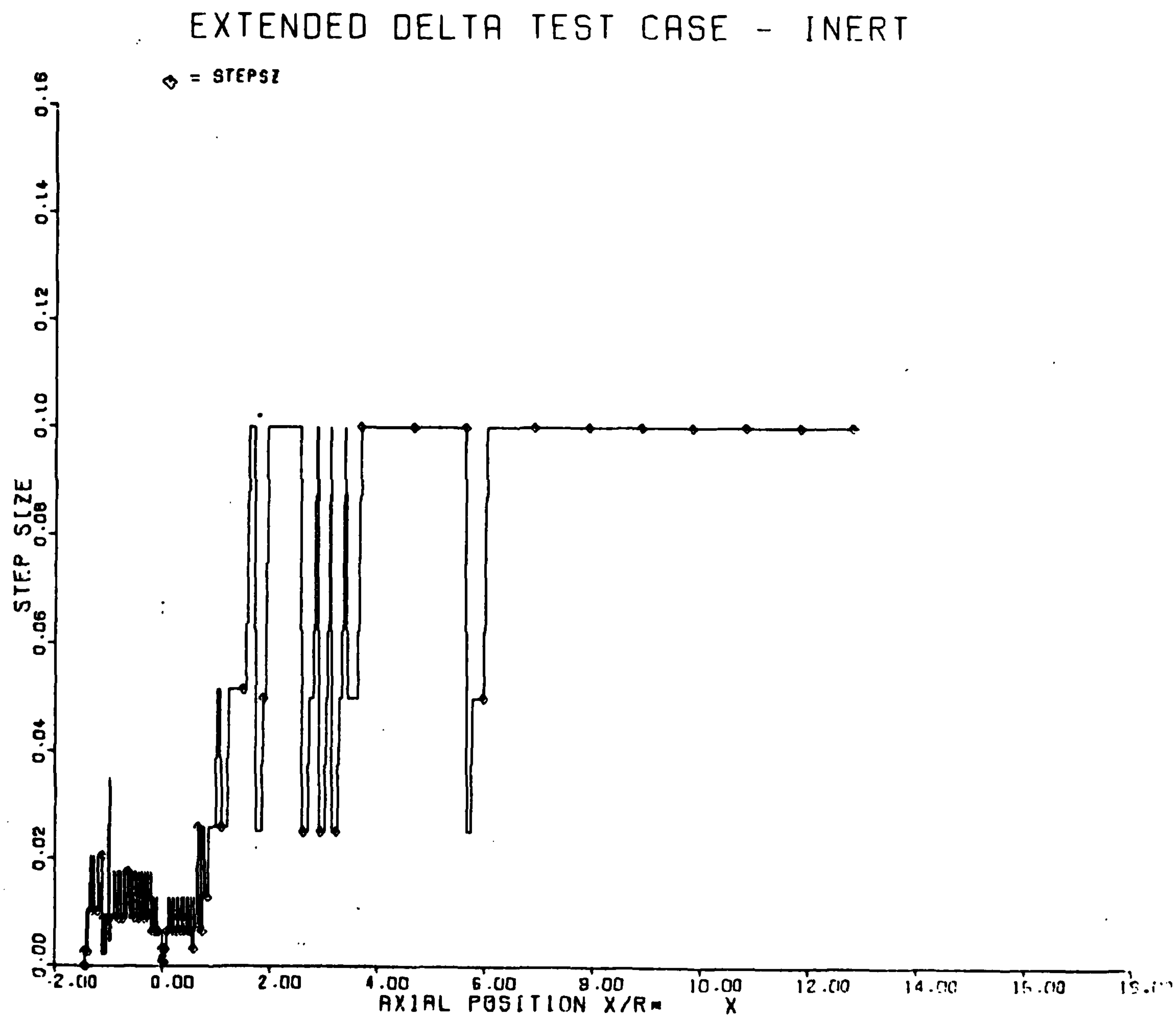
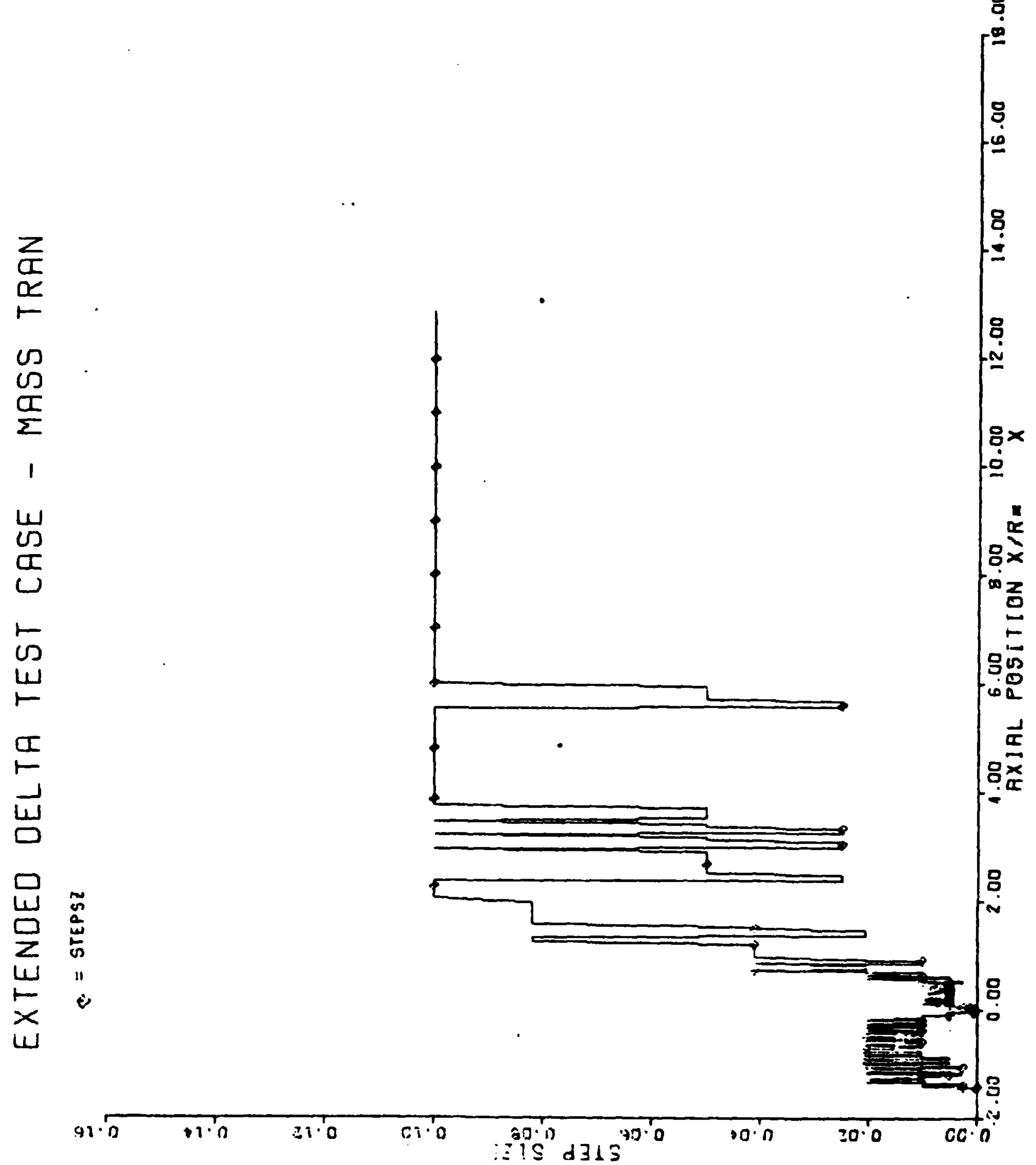
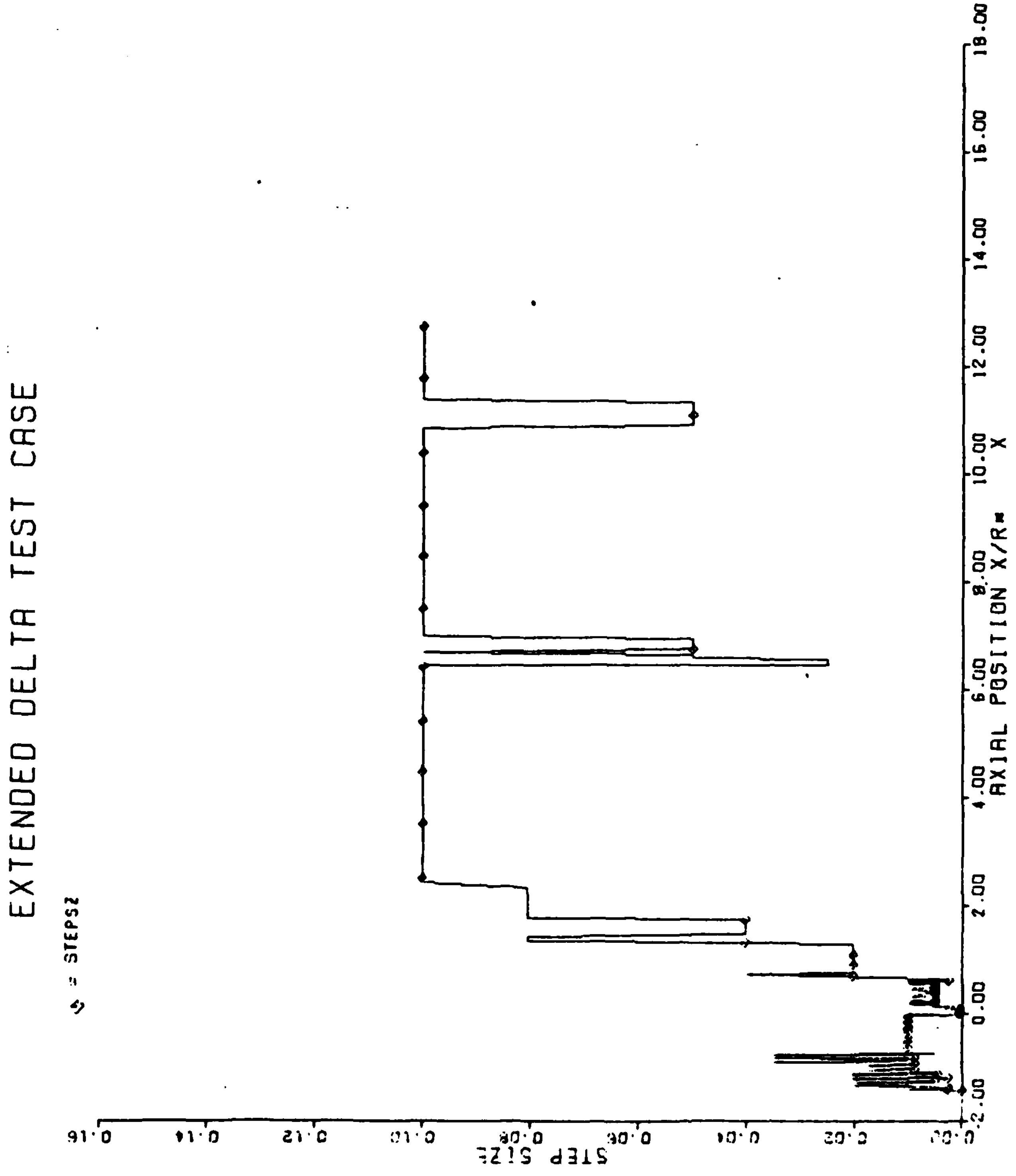
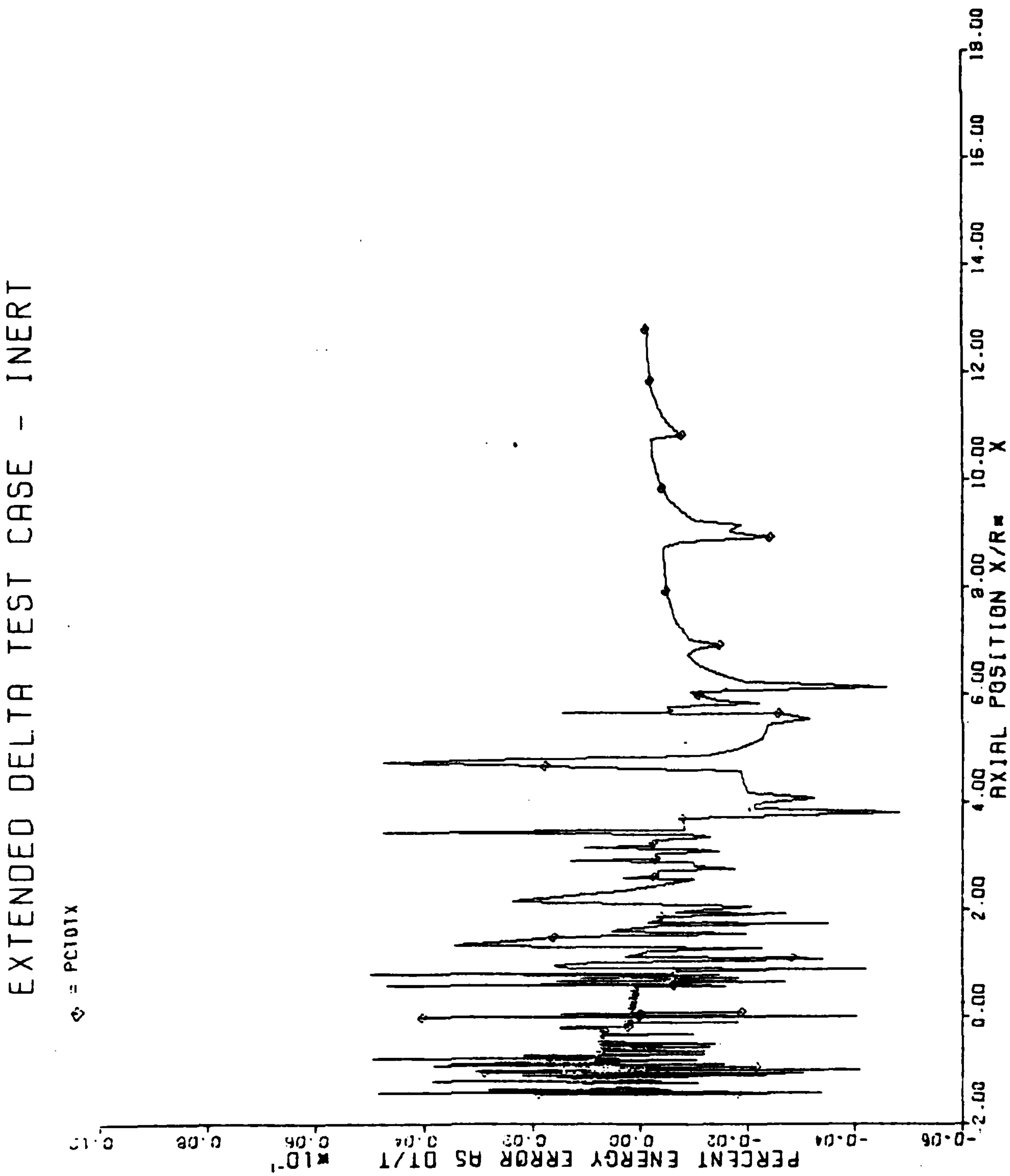
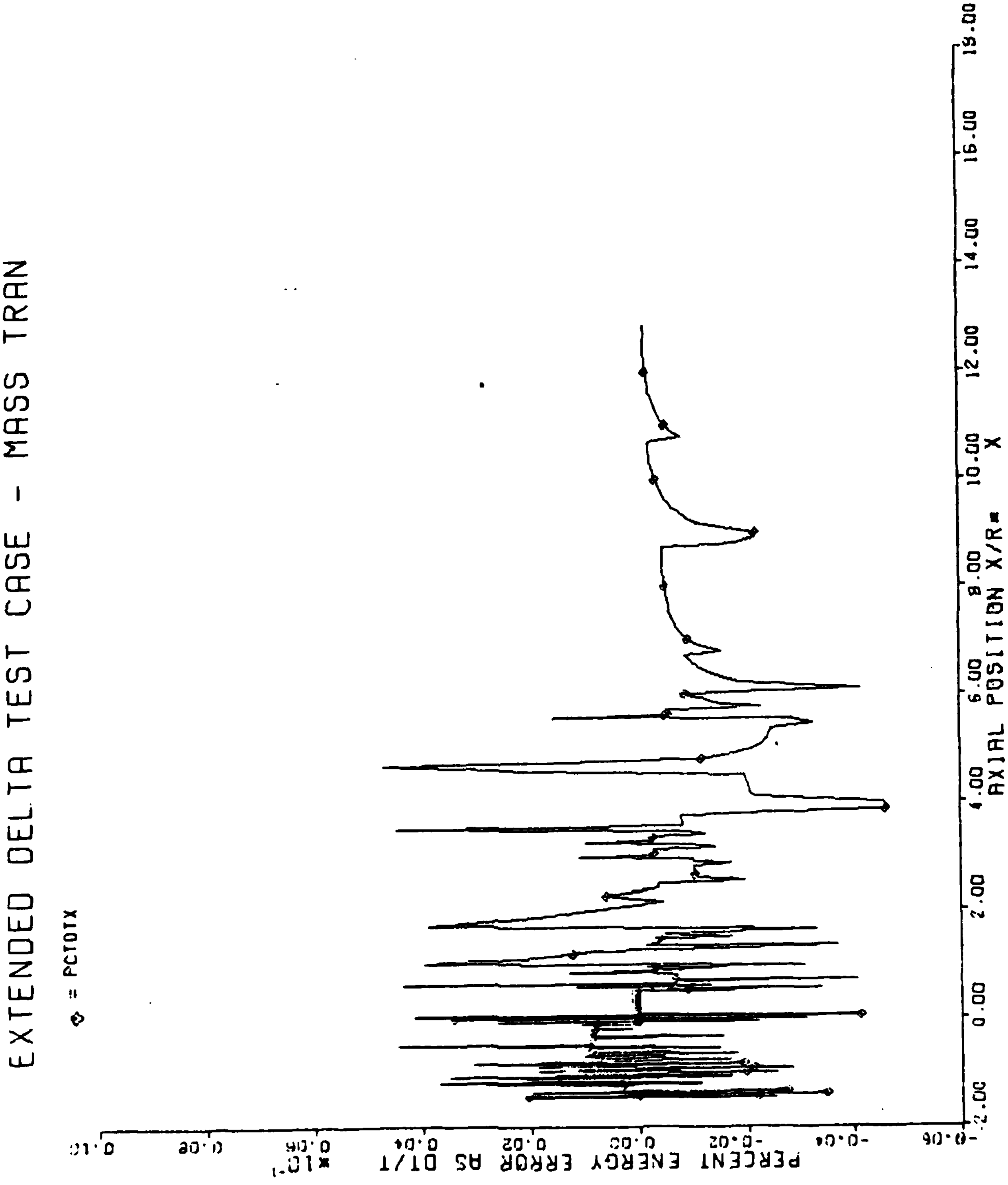

EXTENDED DELTA TEST CASE - INERT
◇ = STEPSZ
STEP SIZE
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
AXIAL POSITION X/R= X


EXTENDED DELTA TEST CASE - MASS TRAN
= STEPSZ
STEP SIZE
AXIAL POSITION X/R= X
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00

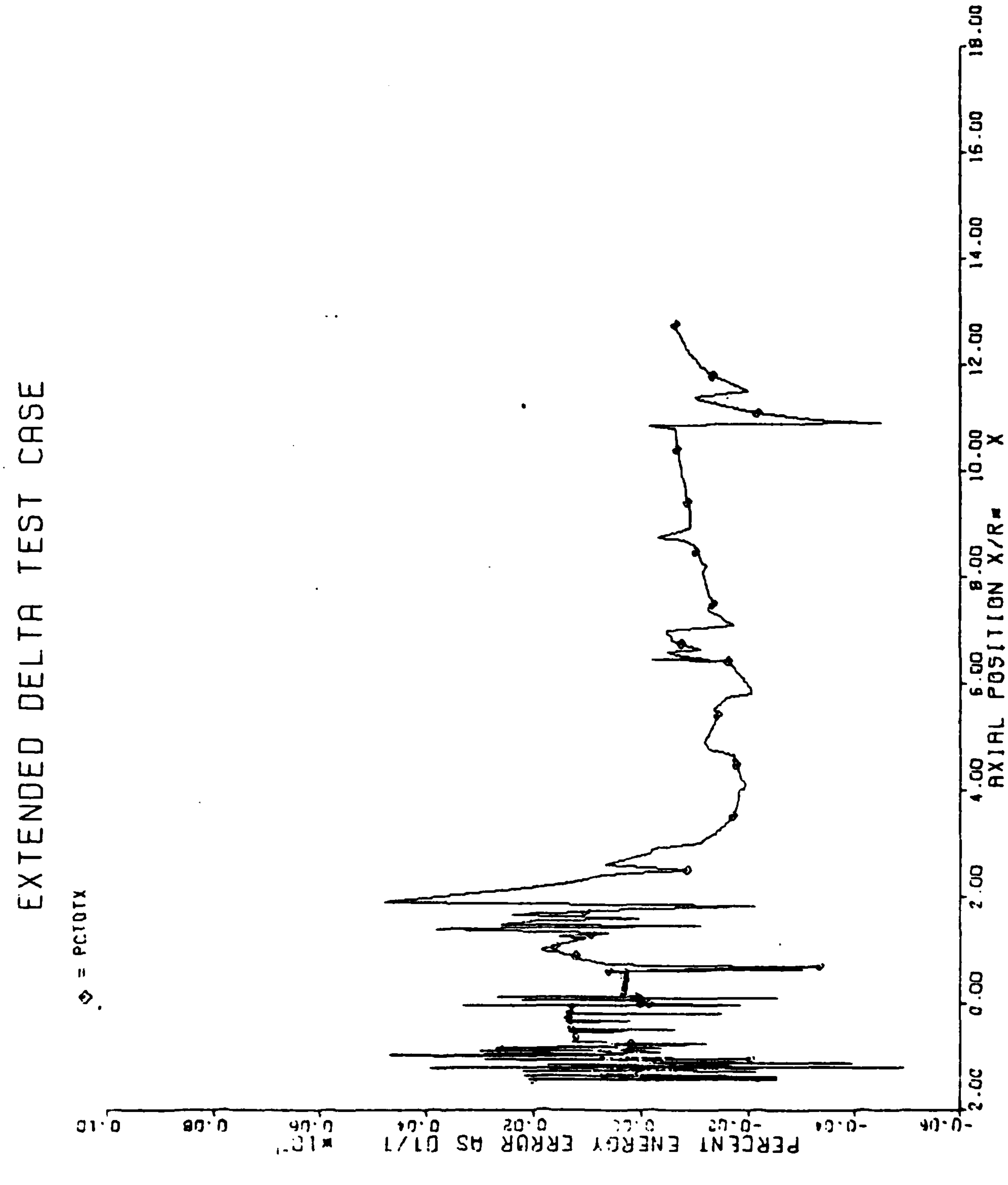

EXTENDED DELTA TEST CASE
◊ = STEPSZ
STEP SIZE
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
AXIAL POSITION X/R* X
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00



EXTENDED DELTA TEST CASE - INERT
◇ = PC101X
PERCENT ENERGY ERROR AS DT/T *10⁻¹
AXIAL POSITION X/R* X
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10

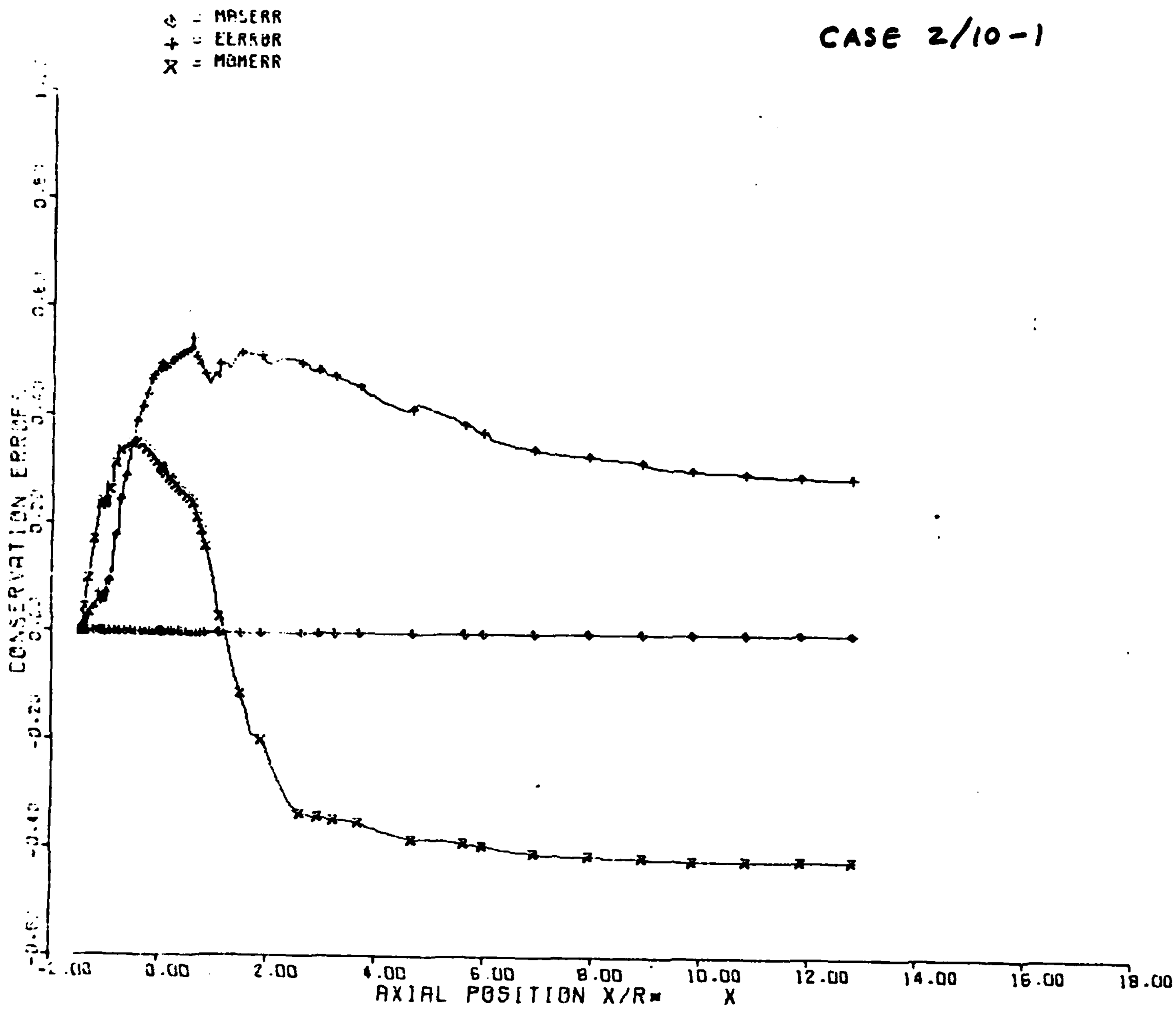


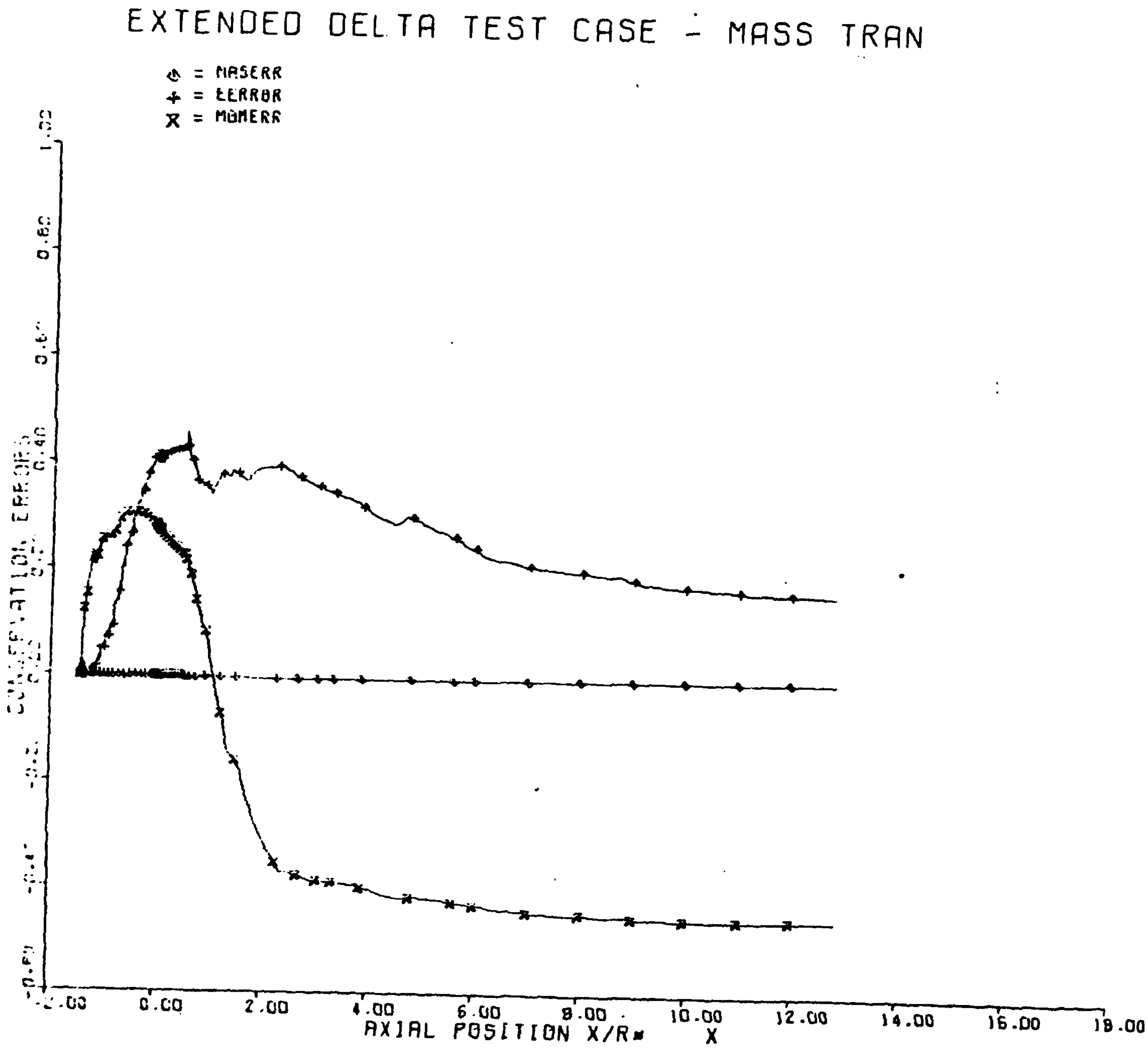
EXTENDED DELTA TEST CASE - MASS TRAN
◇ = PCTOTX
AXIAL POSITION X/R*
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
PERCENT ENERGY ERROR AS DT/T $\times 10^{-1}$
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10

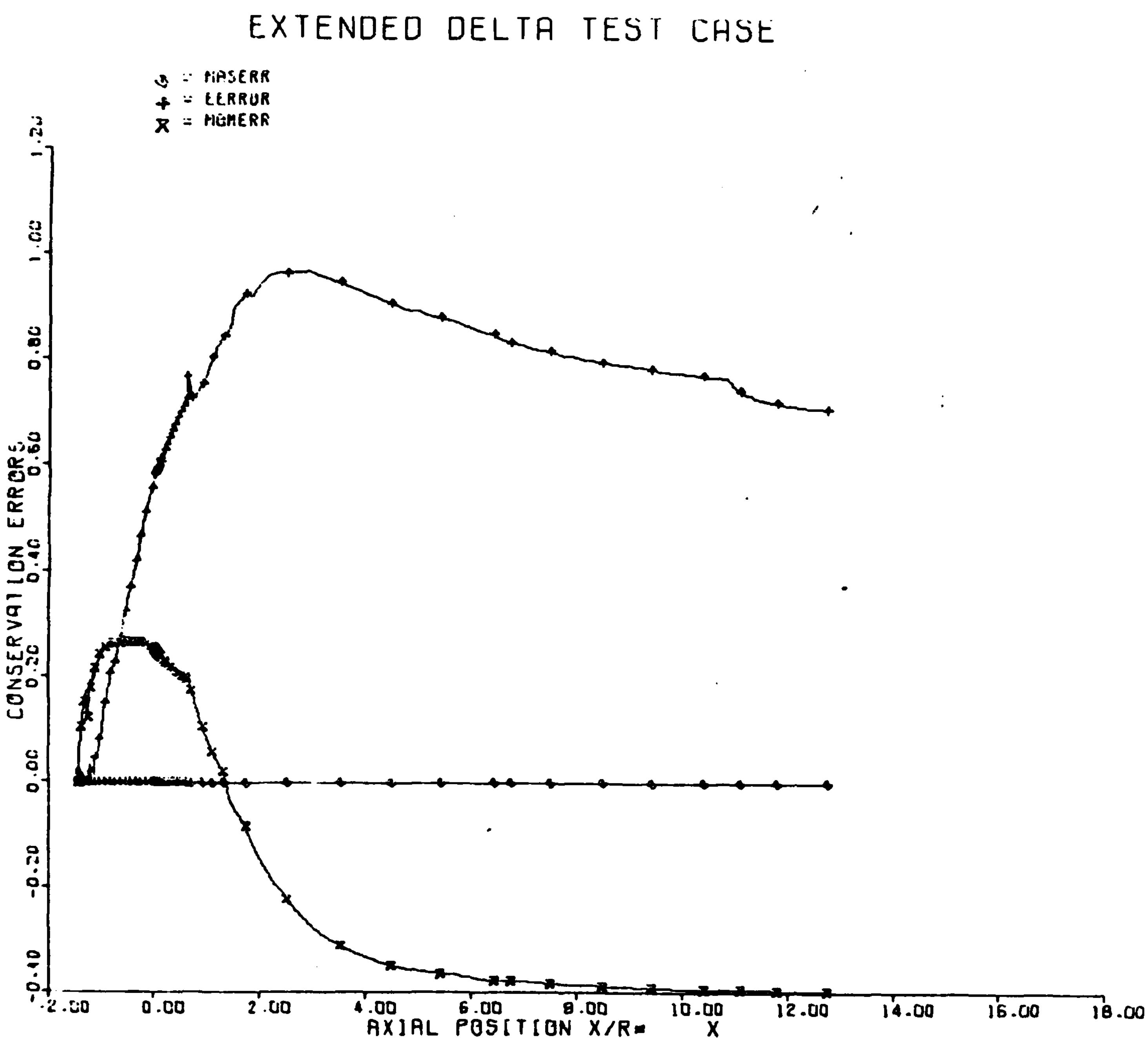

EXTENDED DELTA TEST CASE
◇ = PCTOTX
PERCENT ENERGY ERROR AS Q1/1 ×10⁻¹
AXIAL POSITION X/R× X
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10

EXTENDED DELTA TEST CASE - INERT

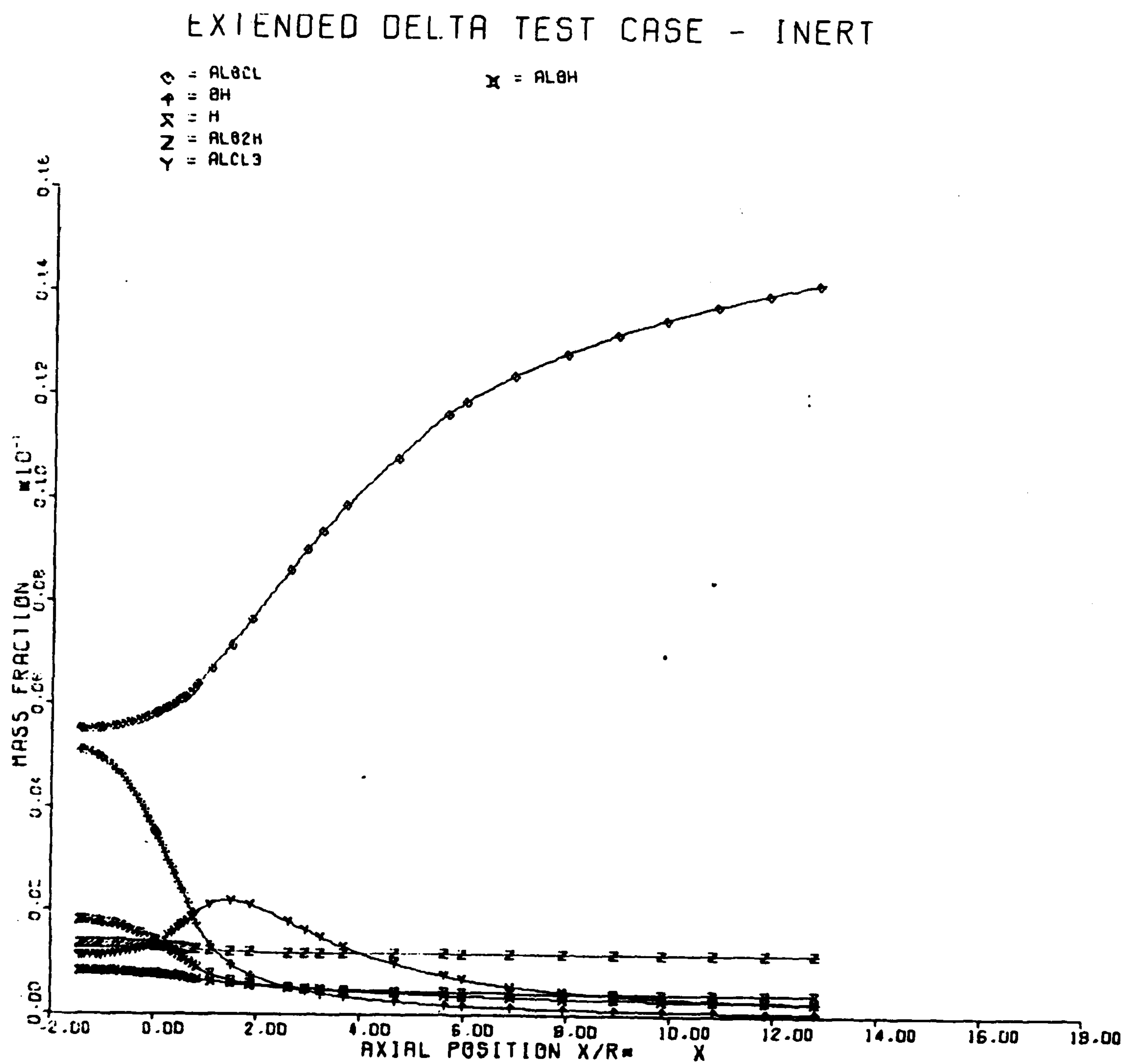
CASE 2/10-1

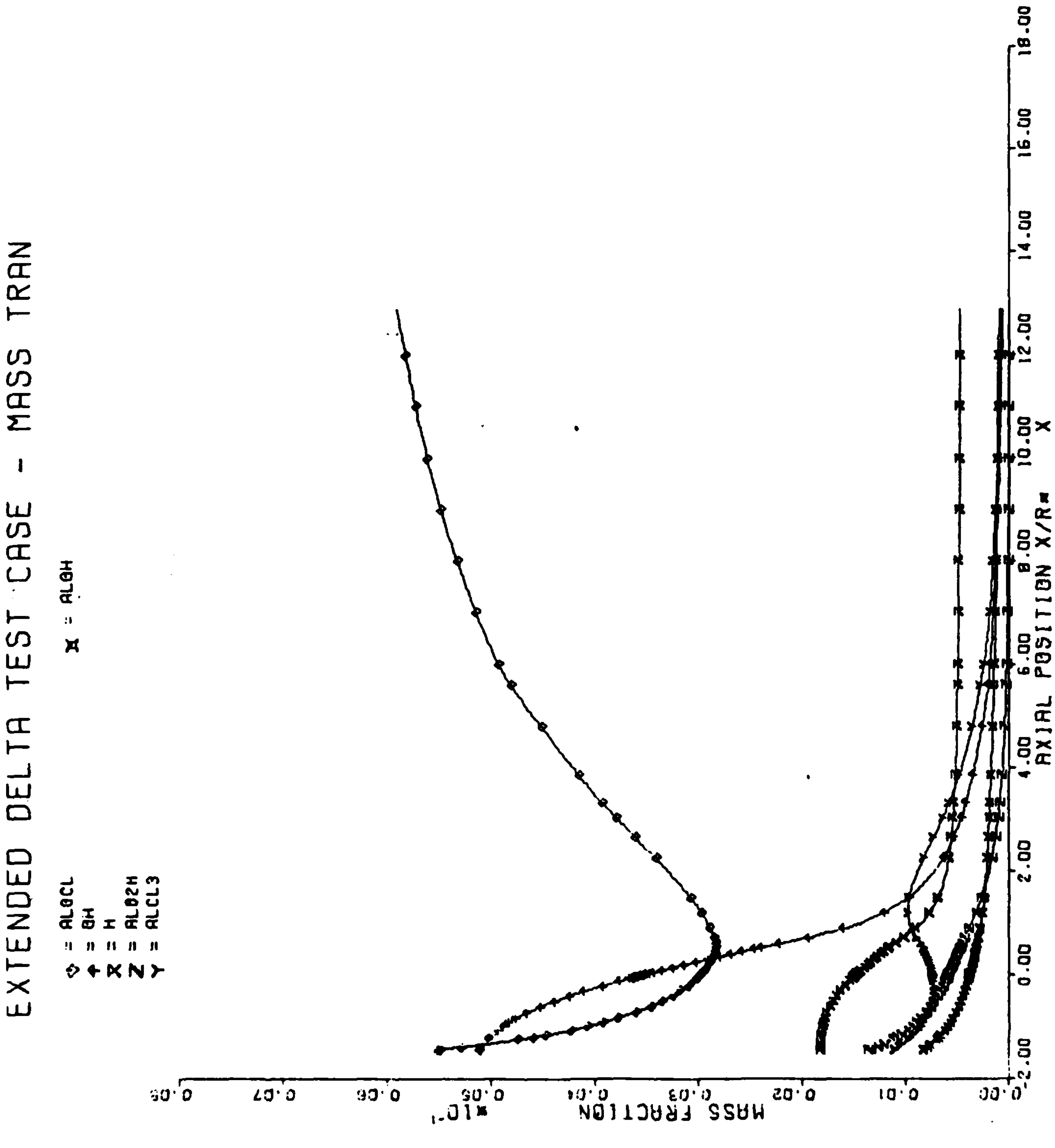


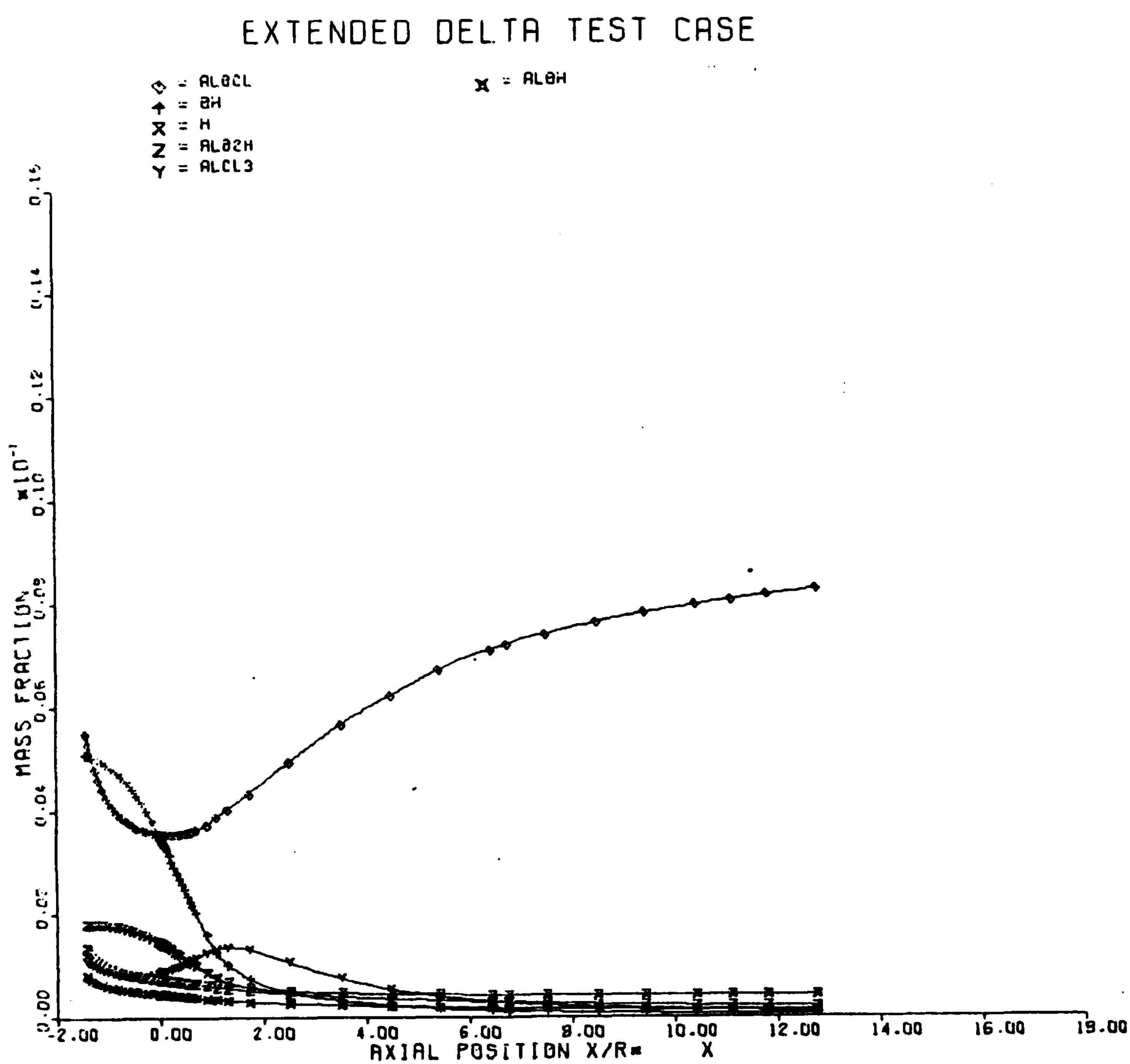

EXTENDED DELTA TEST CASE - MASS TRAN
= MASERR
+ = EERROR
X = MOMERR
CONSERVATION ERRORS
AXIAL POSITION X/R*
X
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
0.40
0.80



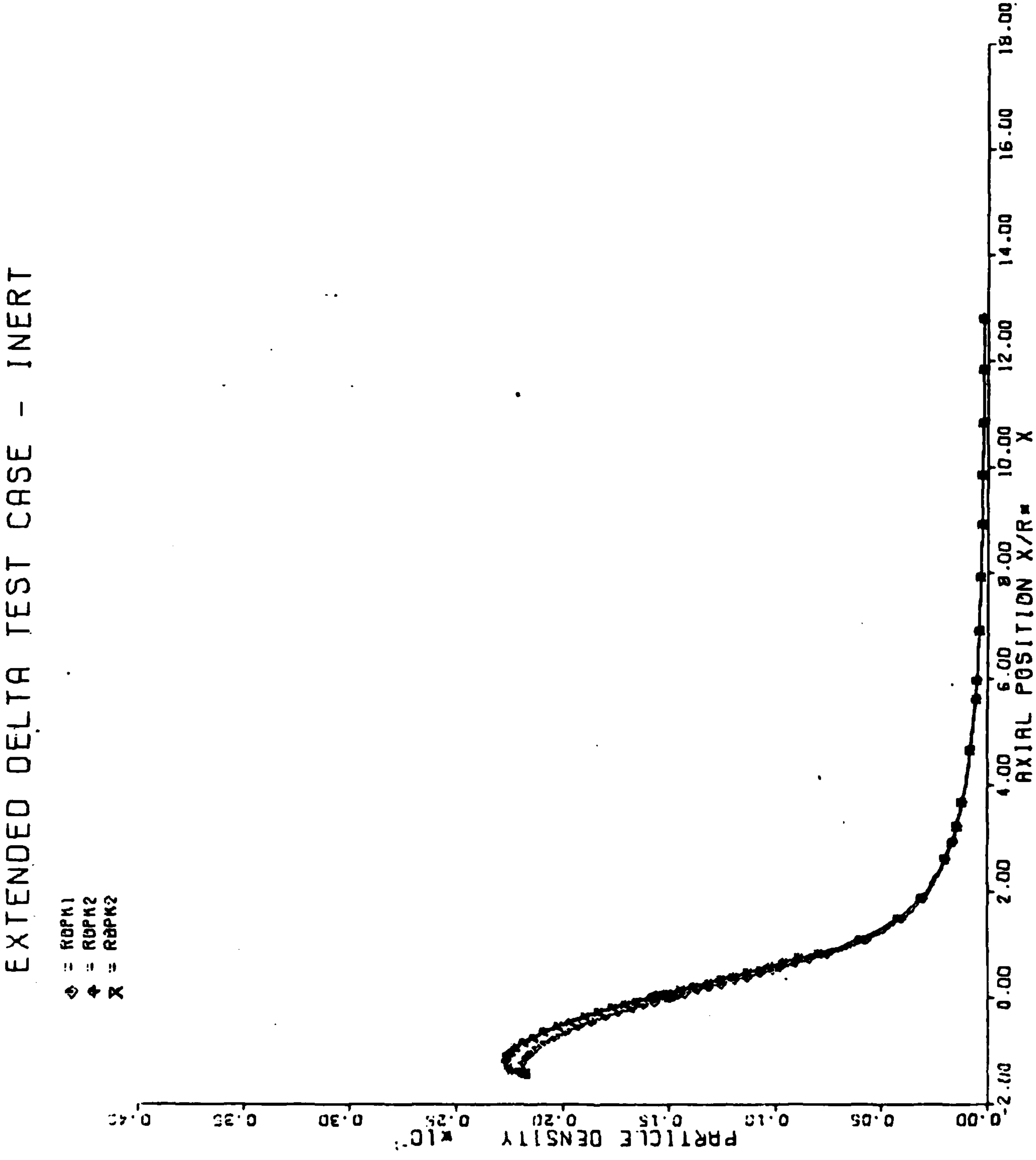
EXTENDED DELTA TEST CASE
= MASERR
= EERROR
= MOMERR
CONSERVATION ERRORS
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
AXIAL POSITION X/R* X


EXTENDED DELTA TEST CASE - INERT
◇ = ALBCL
✢ = BH
X = H
Z = ALB2H
Y = ALCL3
Ӿ = ALBH
MASS FRACTION ×10⁻¹
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
AXIAL POSITION X/R* X


EXTENDED DELTA TEST CASE - MASS TRAN
◇ = ALOCL
+ = OH
X = H
Z = ALO2H
Y = ALCL3
¤ = ALOH
MASS FRACTION *10⁻¹
AXIAL POSITION X/R* X
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00

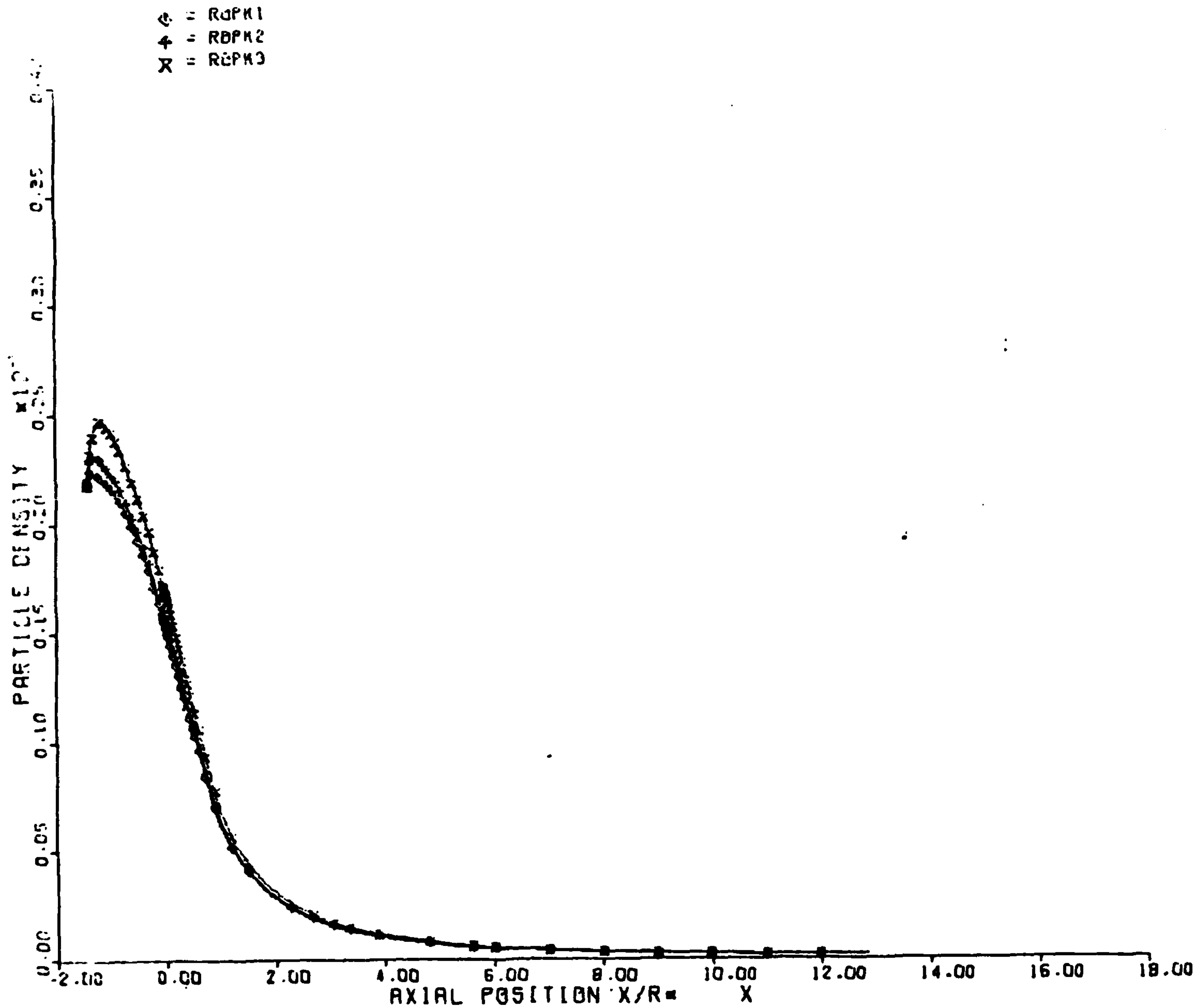


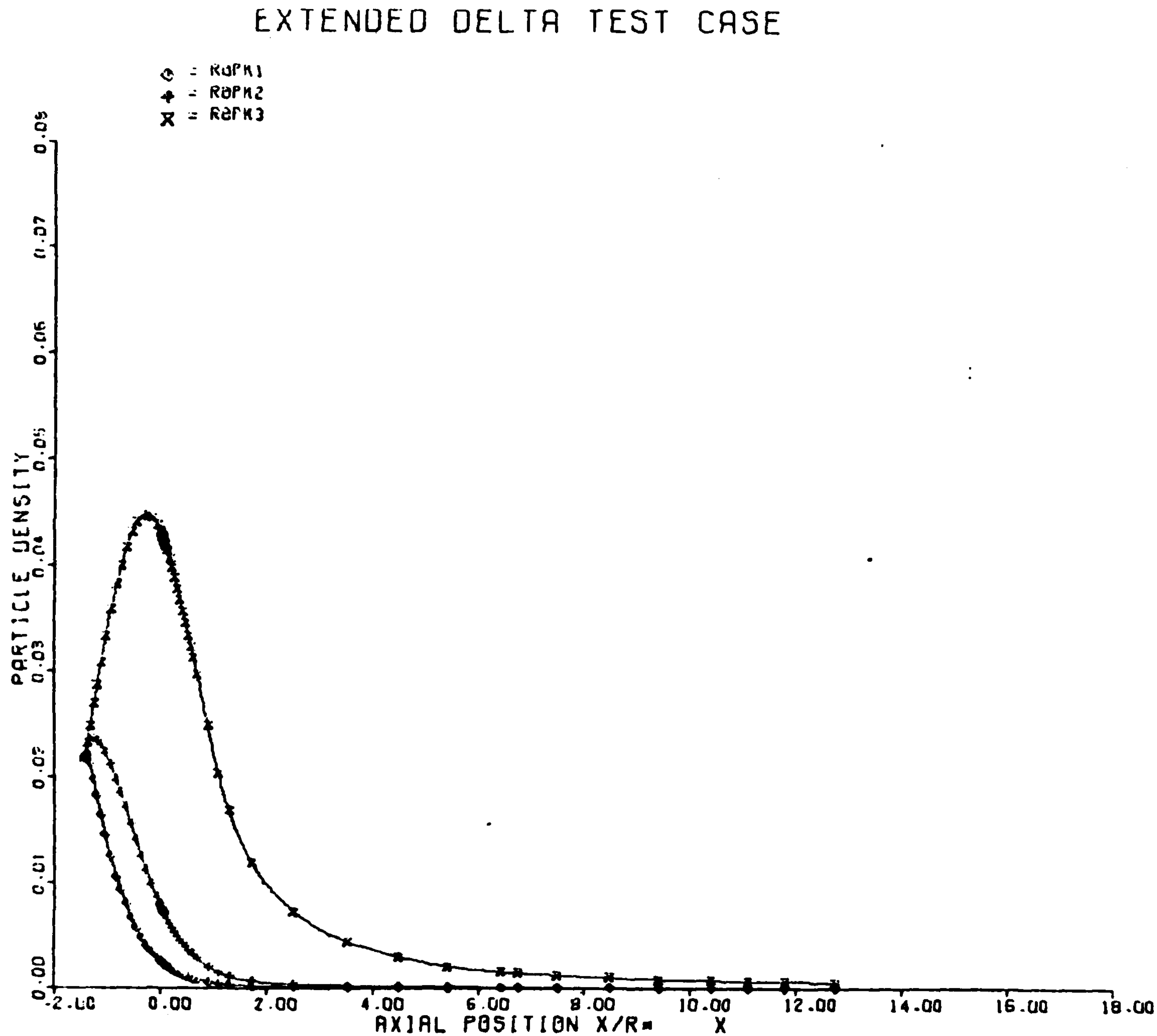
EXTENDED DELTA TEST CASE
◇ = ALOCL
✦ = OH
X = H
Z = ALO2H
Y = ALCL3
✖ = ALOH
MASS FRACTION ×10⁻¹
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
AXIAL POSITION X/R= X



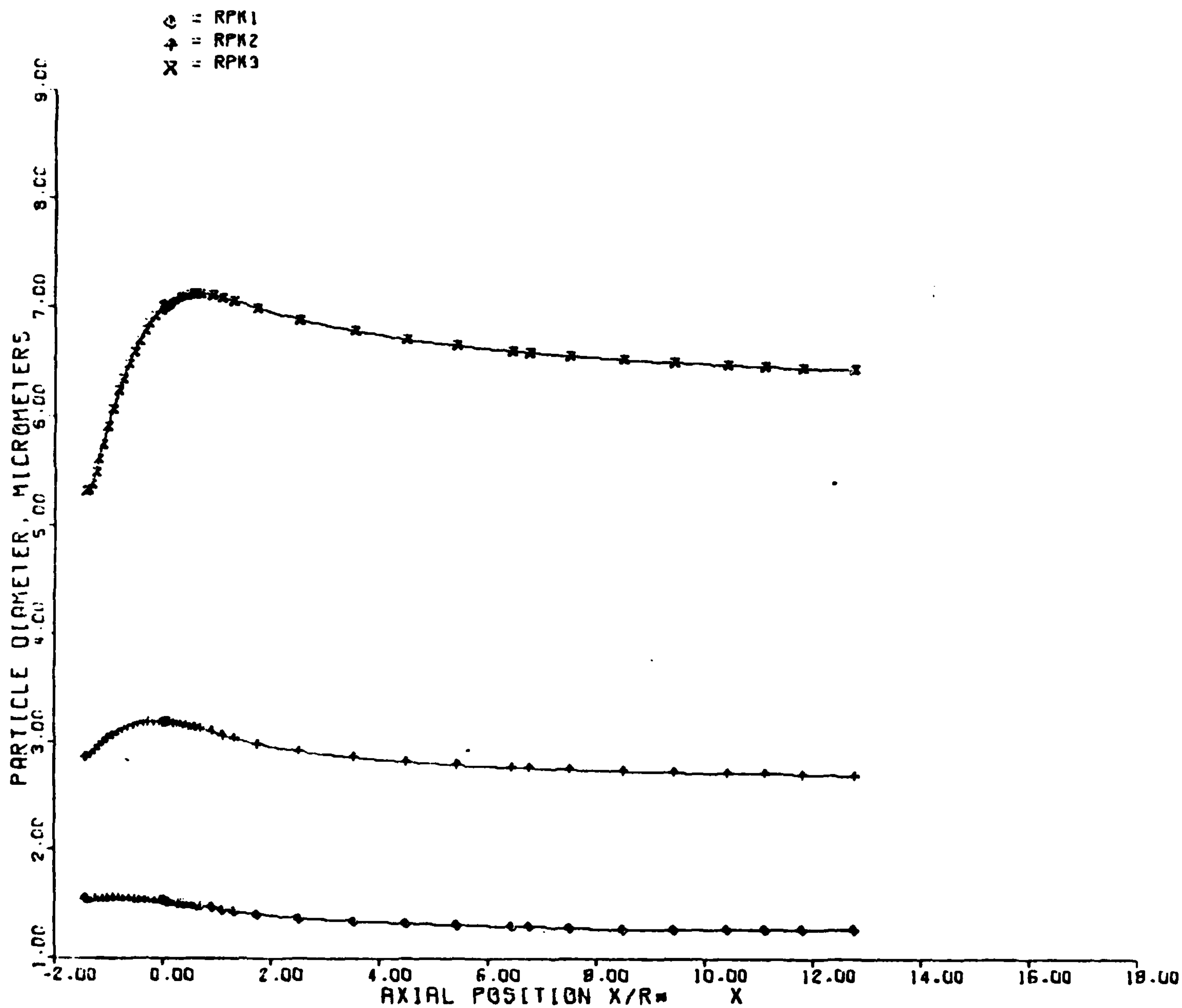
EXTENDED DELTA TEST CASE - INERT
= RBPK1
= RBPK2
= RBPK2
PARTICLE DENSITY
AXIAL POSITION X/R*
X
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

EXTENDED DELTA TEST CASE - MASS TRAN

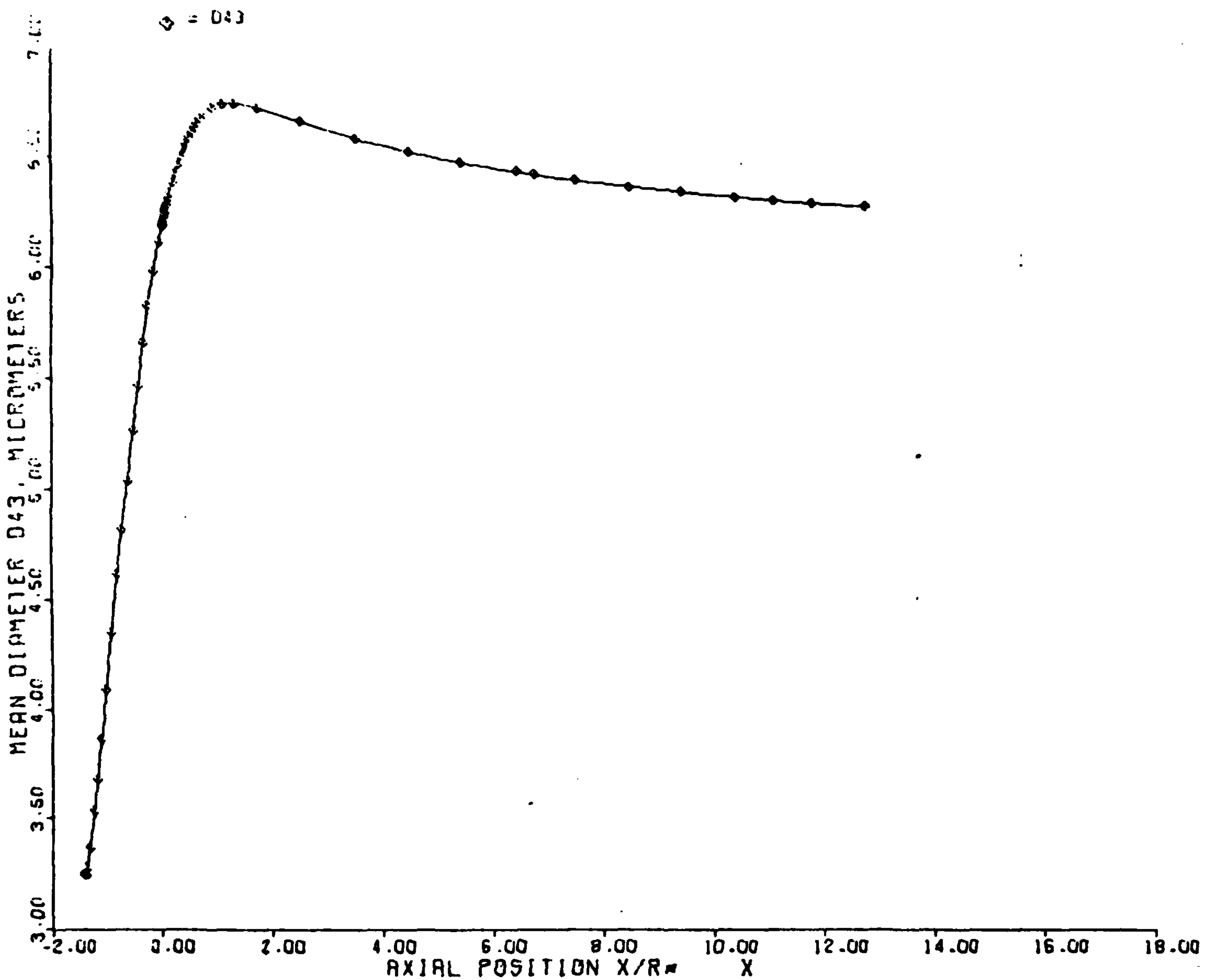


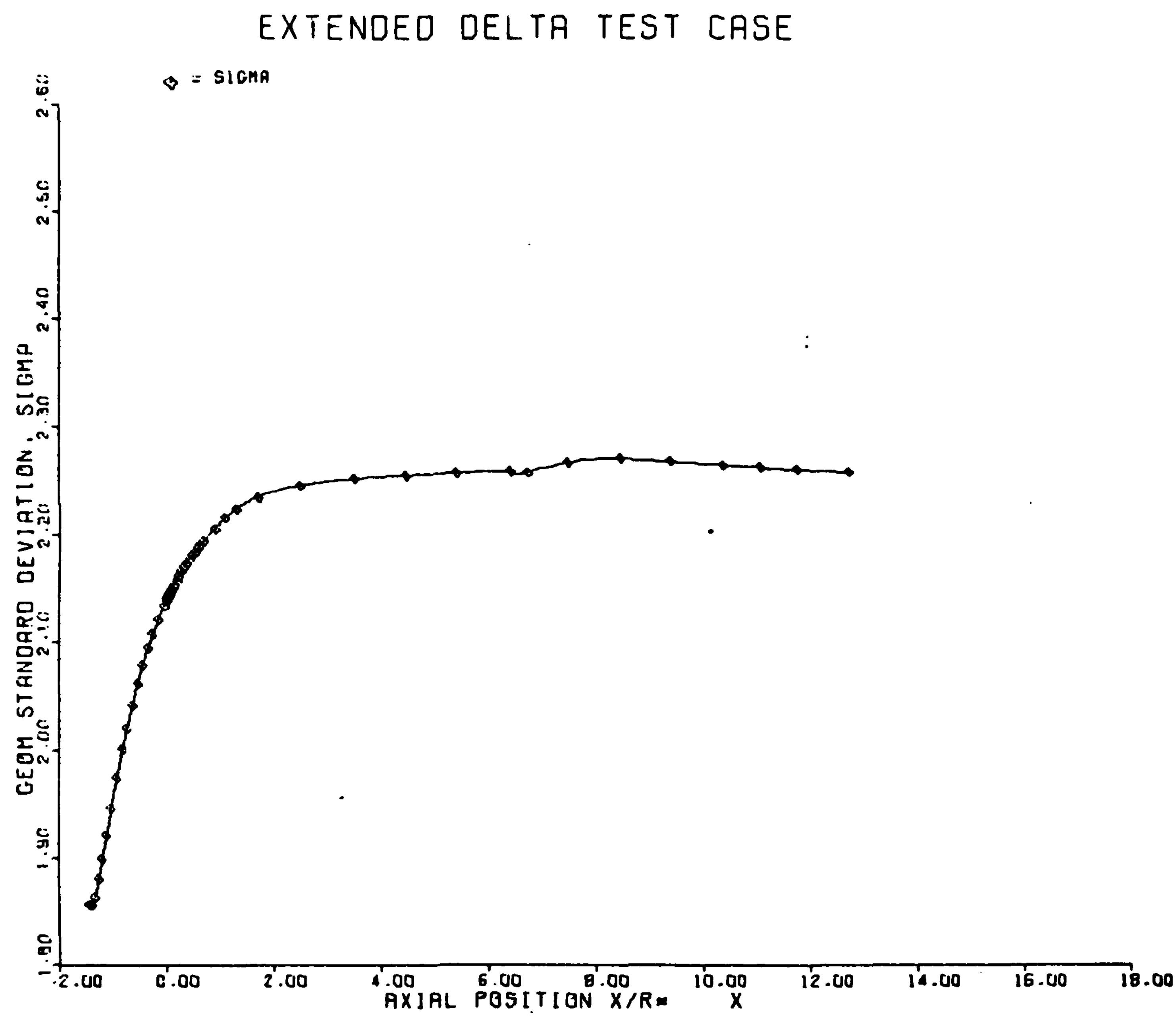

EXTENDED DELTA TEST CASE
◆ = RØPK1
✚ = RØPK2
X = RØPK3
PARTICLE DENSITY
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
AXIAL POSITION X/R= X

EXTENDED DELTA TEST CASE



EXTENDED DELTA TEST CASE





EXTENDED DELTA TEST CASE
◇ = SIGMA
GEOM STANDARD DEVIATION, SIGMA
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
AXIAL POSITION X/R* X

CONCLUSIONS

- OD3P COMPARES WELL WITH SPP-ODK
- TEMP DEFINED SOLUTION - STABILITY
  - LAG ANALYSIS
- PREDICTED LAGS CLOSE TO CONST. FRAC. LAG
- MASS TRANSFER EFFECT ~ +1 SEC
  ABOUT 60% OF EQUIL - RESTR. EQ.
- COLLISIONS DOUBLE MEAN PARTICLE SIZE
- OD3P READY FOR MOTOR CASES AND PARAMETRICS
- OD3P NOT YET READY FOR USE IN SPP

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DROPLET FLOW EXPERIMENTS

PARTICLE IMPACT EROSION
PROGRAM

AFRPL CONTRACT F04611-79-C-0012

PRESENTED BY
ZOHER CHIBA
AT

JANNAF PERFORMANCE STANDARDIZATION SUBCOMMITTEE MEETING
SACRAMENTO, CALIFORNIA

14 FEBRUARY 1980

ACUREX Aerotherm

OVERVIEW

- PROGRAM BACKGROUND
- DROPLET BREAKUP EXPERIMENT
- DROPLET IMPACT EXPERIMENT

ACUREX
Aerotherm

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PARTICLE IMPACT EROSION PROGRAM

BACKGROUND

- OBJECTIVE
  - -- TO DEVELOP A METHODOLOGY TO PREDICT EROSION IN SOLID PROPELLANT ROCKET NOZZLES
- APPROACH
  - -- IDENTIFY KEY EROSION MECHANISMS -- MECHANICAL AND THERMOCHEMICAL
  - -- CONDUCT EXPERIMENTS TO CORRELATE AND MODEL PHENOMENA
  - -- SELECT EXISTING CODES (MODIFYING THEM WHEN NECESSARY) TO PREDICT PARTICLE IMPINGEMENT AND MASS REMOVAL
  - -- INCORPORATE CODES AND MODELS INTO PREDICTION METHODOLOGY

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045743

EXPERIMENTAL WORK

- EXPERIMENTAL WORK FORMS THE BASIS FOR UNDERSTANDING AND MODELING THE KEY MECHANISMS AFFECTING PARTICLE IMPACT EROSION
- MOST OF THE EXPERIMENTAL WORK IS UNIQUE -- BEING PERFORMED FOR THE FIRST TIME TO SIMULATE ROCKET NOZZLE EFFECTS

EXPERIMENT	MECHANISM/PHENOMENA STUDIED
1. DROPLET BREAKUP EXPERIMENT	BREAKUP AND CHANGES IN SIZE DISTRIBUTION OF PARTICLES
2. DROPLET IMPACT EXPERIMENTS	DROPLET RESIDENCE TIMES ON SURFACE
3. CHEMICAL REACTIONS EXPERIMENT	MOLTEN PARTICLE-SURFACE CHEMICAL REACTIONS
4. SUBSONIC EROSION EXPERIMENT	MOLTEN PARTICLE-SURFACE EROSION DUE TO CHEMICAL AND MECHANICAL MASS REMOVAL
5. DET TESTS	MECHANICAL MATERIAL REMOVAL AND DEBRIS SHIELDING EFFECTS
6. ASPC SMALL ROCKET MOTOR TESTS	MECHANICAL MATERIAL REMOVAL AND DEBRIS SHIELDING EFFECTS

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J45240

DROPLET BREAKUP EXPERIMENT

OBJECTIVE: TO DETERMINE THE CONDITIONS UNDER WHICH BREAKUP OCCURS AND THE RESULTANT DROPLET SIZE DISTRIBUTION

PURPOSE: TO ESTIMATE THE PARTICLE SIZES IMPACTING WALLS IN NOZZLE THROAT AND EXIT REGIONS

APPROACH:

- SIMULATE PARAMETERS GOVERNING BREAKUP IN ROCKET NOZZLES
- GRADUALLY ACCELERATE FLOW IN COLD FLOW CHANNEL
- USE LASER FRAMING CAMERA TO OBTAIN HIGH RESOLUTION PHOTOGRAPHS

DIMENSIONLESS PARAMETERS:

- RATIO OF DRAG TO SURFACE TENSION FORCES ON DROPLET

  WEBER NUMBER, $We = \frac{\rho_g D_p (u_g - u_p)^2}{\sigma_p}$

- RATIO OF ACCELERATION TO SURFACE TENSION FORCES ON DROPLET

  BOND NUMBER, $Bo = \frac{a_p \rho_p D_p^2}{4\sigma_p}$

- RATIO OF TIME TO CHARACTERISTIC DEFORMATION TIME

  DIMENSIONLESS TIME, $T = \int_0^t \frac{(u_g - u_p)}{D_p} \sqrt{\frac{\rho_g}{\rho_p}}\, dt$

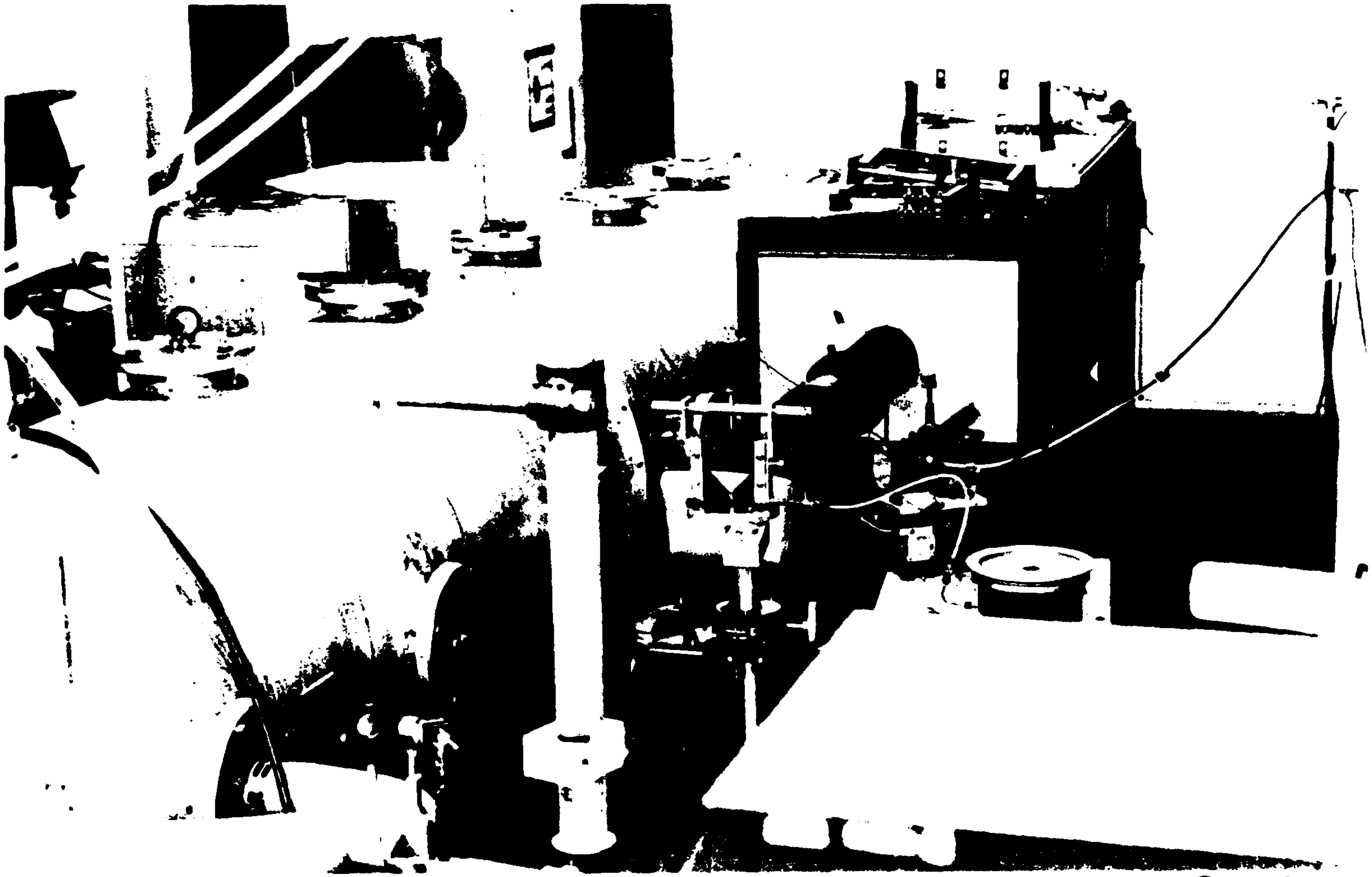
ACUREX Aerotherm

045221

DROPLET BREAKUP EXPERIMENT

AS/S-644b

EXPERIMENTAL APPARATUS

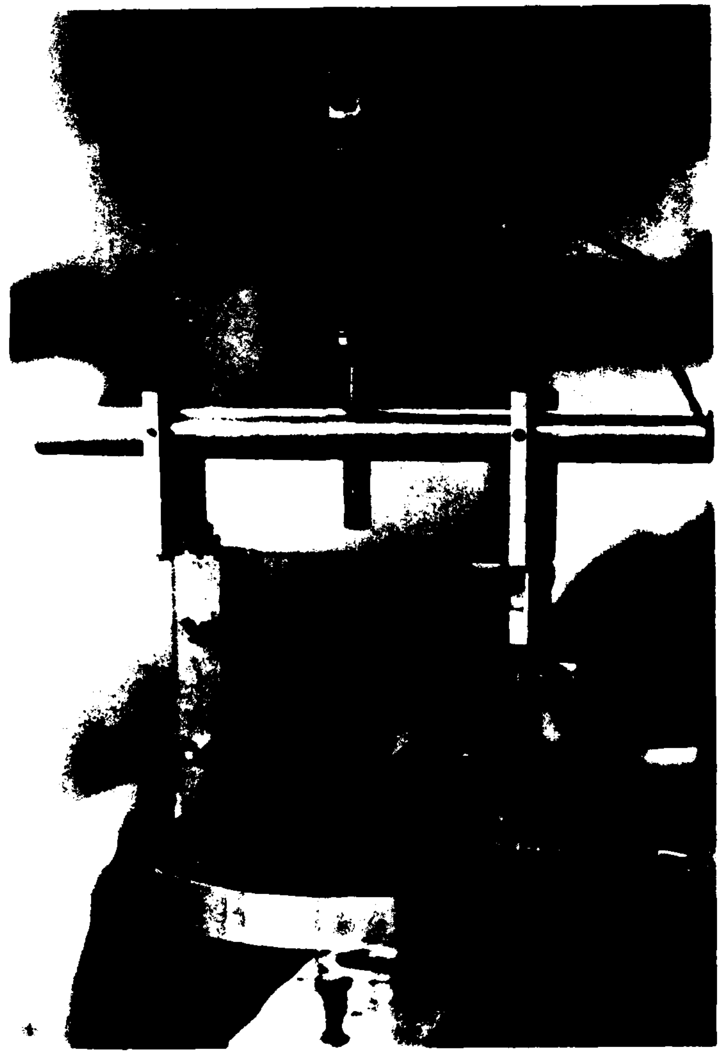


ACUREX Aerotherm

DROPLET BREAKUP EXPERIMENT

AS/S-643b

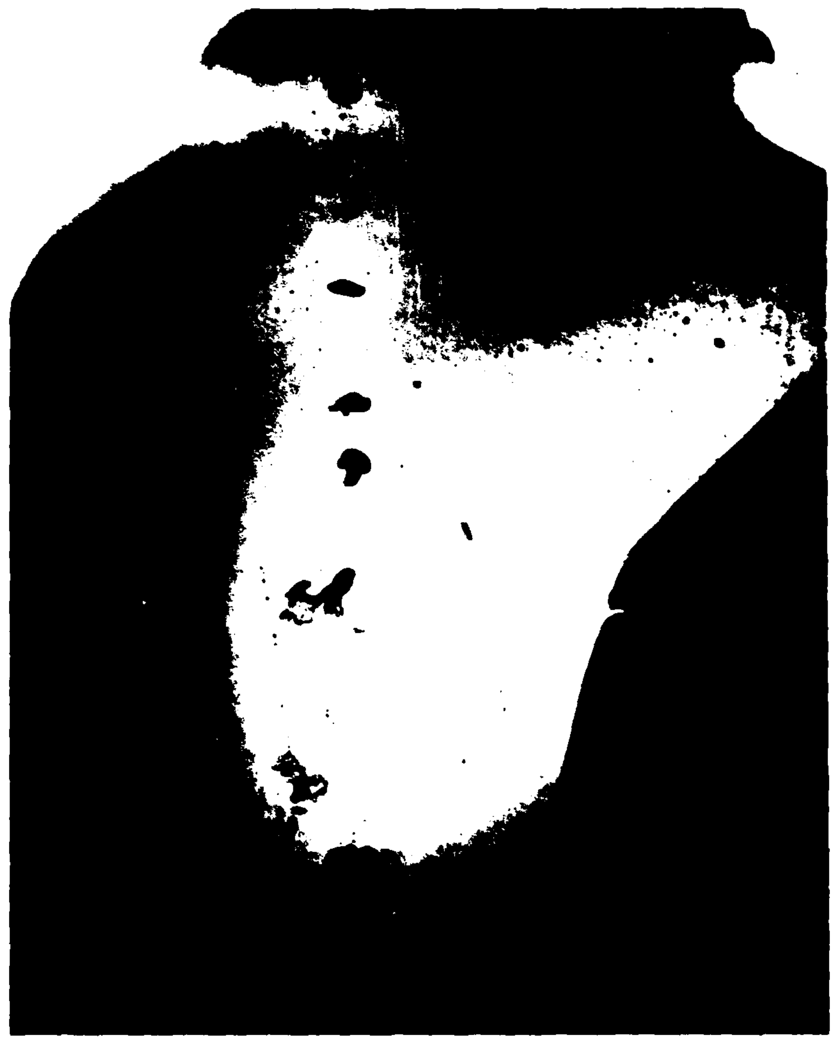
FLOW CHANNEL AND DROPLET GENERATOR



ACUREX Aerotherm

DROPLET BREAKUP EXPERIMENT

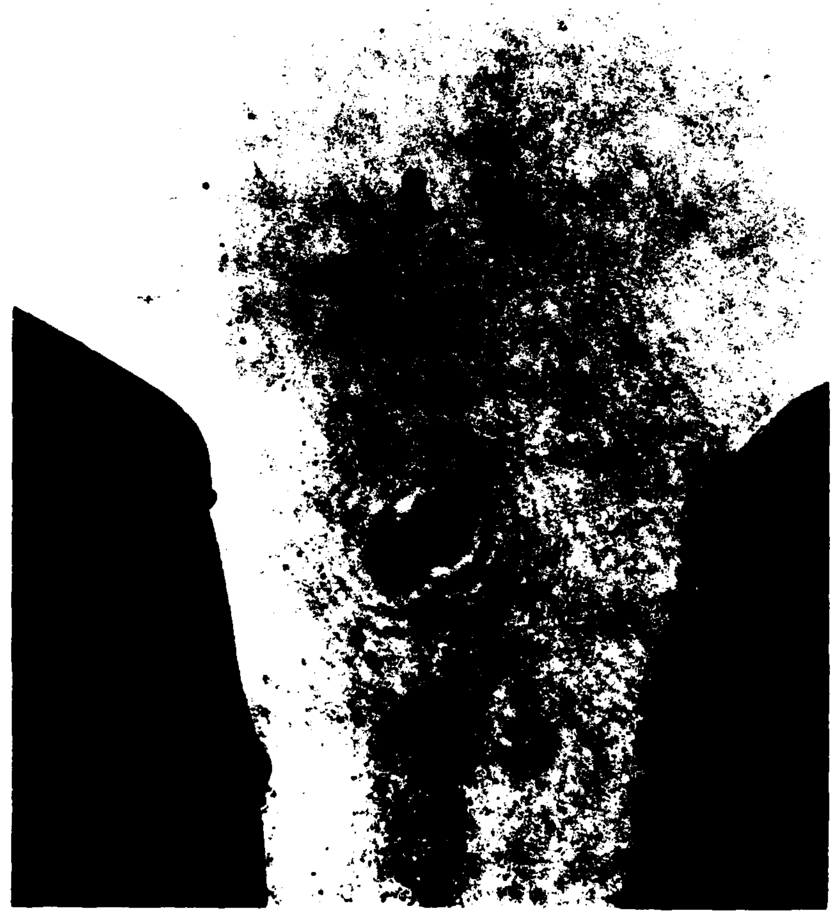
AS/S-641b



ACUREX
Aerotherm

DROPLET BREAKUP EXPERIMENT

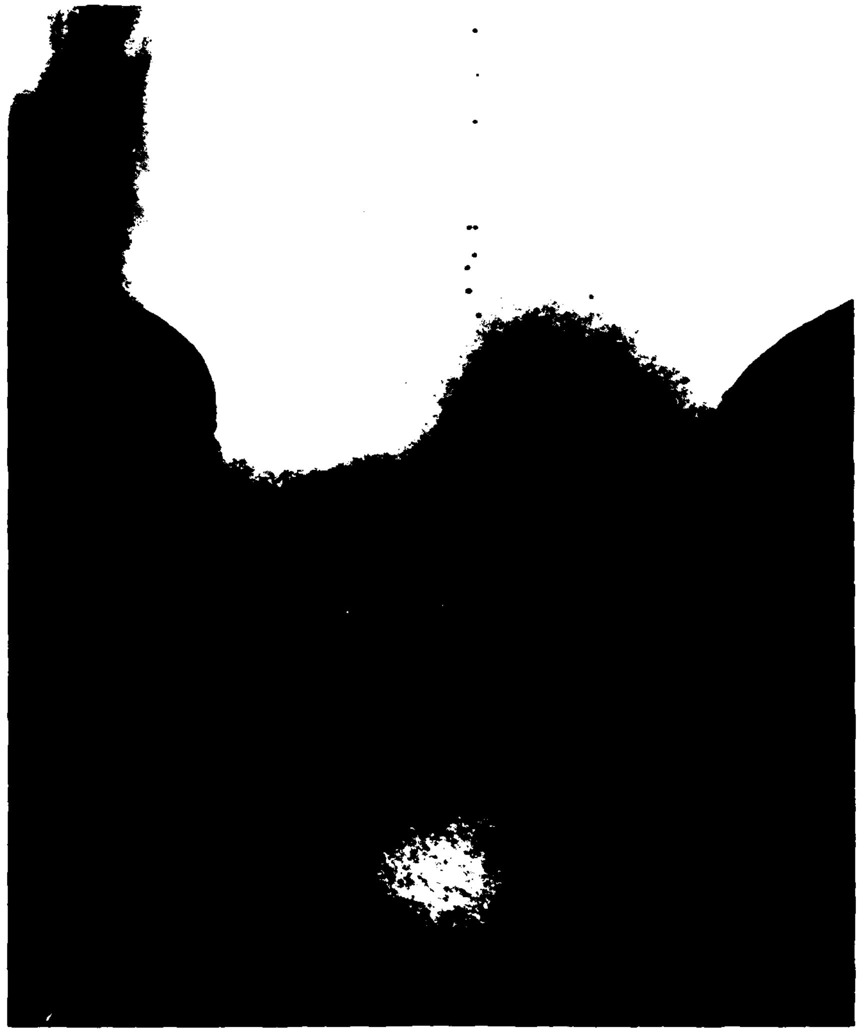
AS/S-642b



ACUREX Aerotherm

DROPLET BREAKUP EXPERIMENT

AS/S-638b



ACUREX Aerotherm

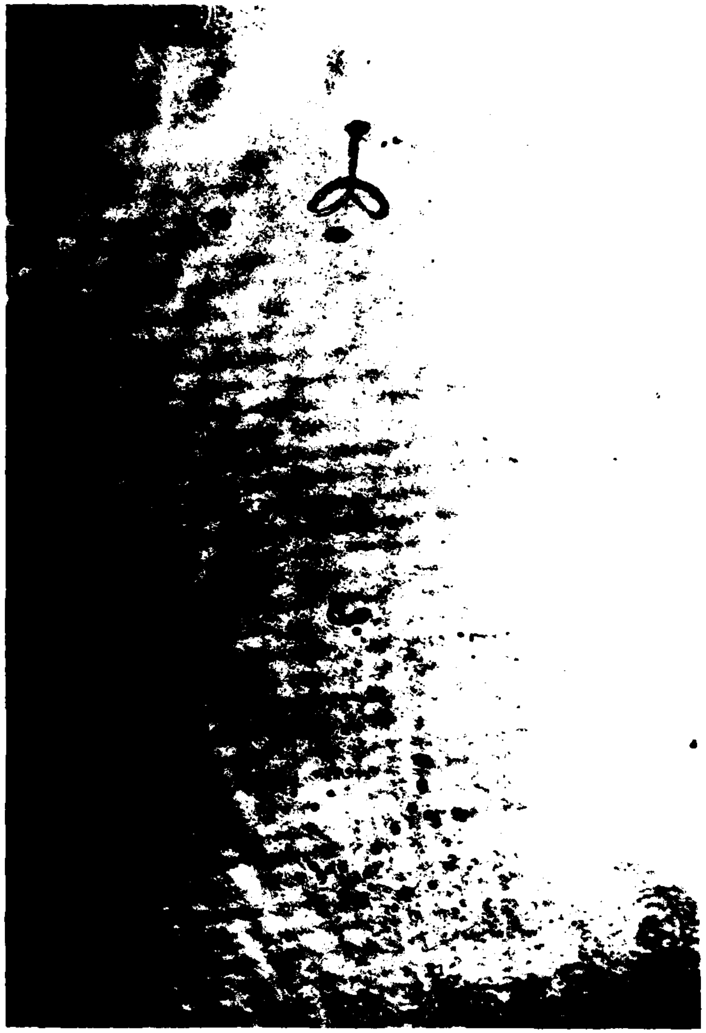
DROPLET BREAKUP EXPERIMENT

AS/S-639b

ACUREX Aerotherm

DROPLET BREAKUP EXPERIMENT

AS/S-640b



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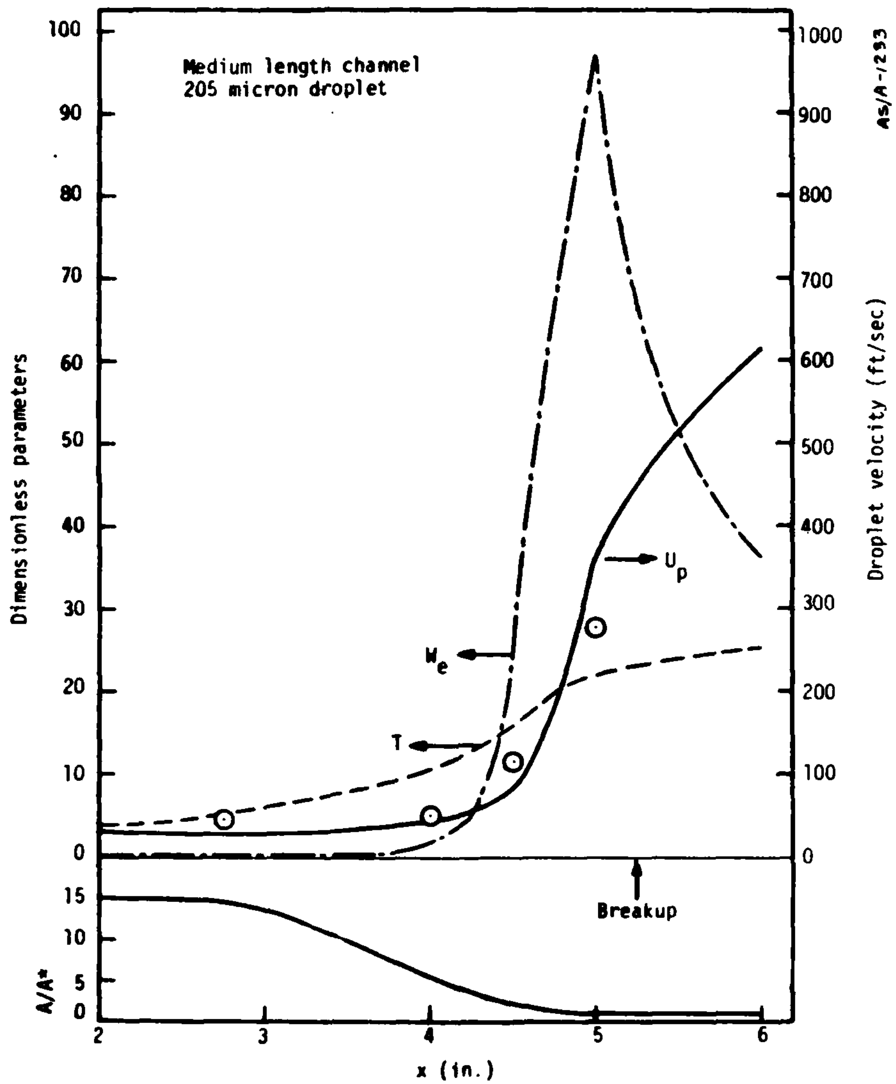
DROPLET BREAKUP EXPERIMENT

PRELIMINARY RESULTS



ACUREX Aerotherm
045751

DROPLET BREAKUP EXPERIMENT

SUMMARY

- OBTAINED DROPLET BREAKUP DATA FOR ROCKET NOZZLE CONDITIONS
- PRELIMINARY CONCLUSIONS: BOTH WEBER NUMBER AND DIMENSIONLESS TIME MUST BE ACCOUNTED FOR TO MODEL BREAKUP PHENOMENA

ACUREX Aerotherm

04575[illegible]

DROPLET IMPACT EXPERIMENTS

OBJECTIVE: TO DETERMINE FEASIBILITY OF OBTAINING EXPERIMENTAL IMPACT DATA IN NOZZLE FLOWS

APPROACH:

- USE COLD FLOW CHANNEL WALL FOR IMPACT EXPERIMENTS
- MEASURE MASS FRACTION OF PARTICLES FLOWING ALONG WALL AFTER IMPACT
- USE LASER FRAMING CAMERA FOR SELECTED HIGH RESOLUTION PHOTOGRAPHS

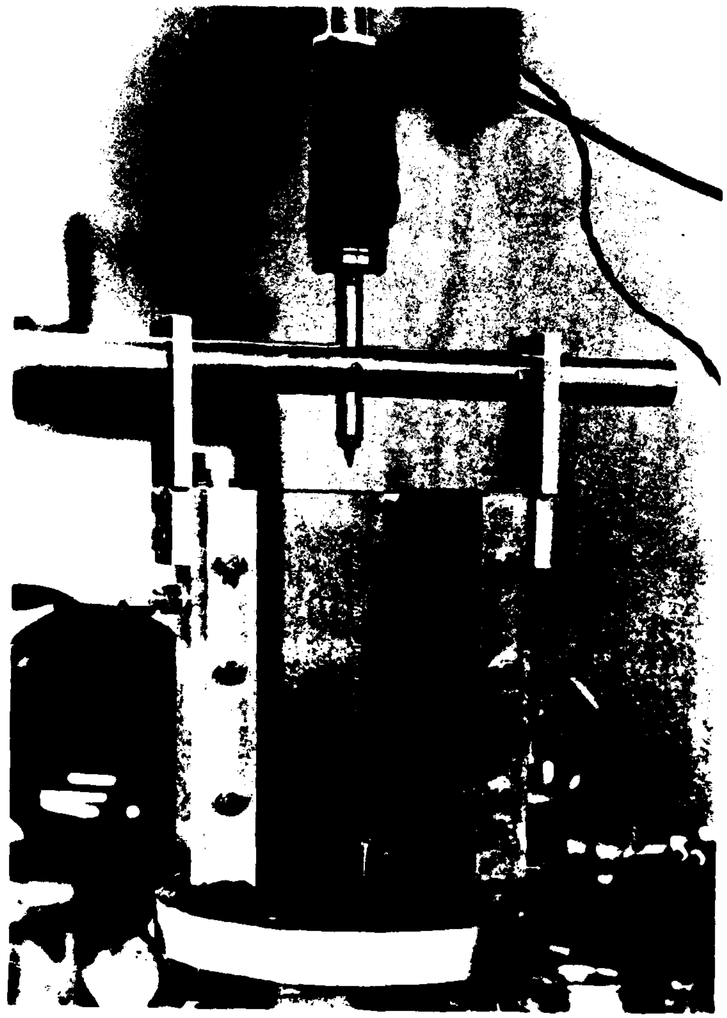
ACUREX Aerotherm

045753

DROPLET IMPACT EXPERIMENT

AS/S-645b

FLOW CHANNEL AND DROPLET GENERATOR



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DROPLET IMPACT EXPERIMENT

AS/S-647b

SMOOTH WALL

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DROPLET IMPACT EXPERIMENT

AS/S-646b

ROUGH WALL

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DROPLET IMPACT EXPERIMENT

SUMMARY

DEMONSTRATED FEASIBILITY OF OBTAINING EXPERIMENTAL IMPACT DATA IN NOZZLE FLOWS

ACUREX Aerotherm

045754

PERFORMANCE PREDICTION METHODOLOGY

STATUS SUMMARY

Joe D. Hoffman

Purdue University

February 1980

Performance Prediction Methodology Status Summary

Performance — Specific impulse, Isp

Theoretical performance — Maximum Isp with no losses, Isp_{th}

Losses — Decrement in Isp due to real effects, ΔIsp_{loss}

Delivered performance — Isp including losses, Isp_D

The objective of the performance prediction methodology is to a priori predict Isp_D within ± 0.5%.

Theoretical performance, Isp_{th}, is determined by a one-dimensional, isentropic (i.e., adiabatic and frictionless), equilibrium expansion from equilibrium combustor conditions. This calculation is accomplished with the NASA Lewis thermochemistry program known as ODE.

LOSSES

Two-dimensional loss	0.1 to 3%
Finite rate kinetics loss	0.05 to 10%
Two-phase flow loss	0 to 5%
Boundary layer loss	0.5 to 5%
Erosion loss	0 to 2%
Submergence loss	0 to 1%
Combustor efficiency	0 to 5%

$$Isp_D = Isp_{th} - \sum \Delta Isp_{loss}$$

$$Isp_D = Isp_{th} \; \pi \, \eta_{loss}$$

$$Isp_D = Isp_{th} \; \pi \, \eta_{loss} - \Delta Isp_{BL}$$

Table 2-1 Interaction of Physical Phenomena with Performance Loss Calculations

PERFORMANCE LOSSES / PHENOMENA	Divergence Loss	Boundary Layer Loss	Kinetic Loss	Two-Phase Flow Loss	Combustion Inefficiency
Non One-Dimensional Flow		1	2	2	3
Viscosity And Thermal Conductivity	3		3	2	3
Finite Rate Chemistry	3	2		3	3
Multiphase Flow	1	2	2		3
Incomplete Combustion	3	2	2	3	

Legend:

1. Primary Importance (could be $>$ 0.2% effect on I_{sp})
2. Secondary Importance (probably $<$ 0.2% effect on I_{sp})
3. Generally Not Important

Loss Calculations

Loss Model - Performance calculation with a model containing certain mechanisms including a particular loss.

Reference Model - Performance calculation with a model containing the same mechanisms except the loss in question.

Problems - Selection of the losses to be separated or coupled.
Establishment of the loss models - very subjective.
How to make references model calculations.

COMBUSTION EFFICIENCY

$$I_{SP_D} = I_{SP_{TH}} \; \eta_{CE} \; \eta_{ER} \; \eta_{KIN} \; \eta_{SUB} \; \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\eta_{CE} \equiv I'_{SP} / I_{SP_{TH}}$$

WHERE

$$I'_{SP} = I'_{SP} (\bar{F})$$

$$\bar{F} = \text{MASS FRACTION OF UNBURNED AL}$$

NOTES:

CORRELATION OF COMPUTER RESULTS

HAS BEEN CALIBRATED USING DATA

ALUMINIZED PROPELLANTS ONLY

6% UNBURNED AL GIVES ≈ 1% PERFORMANCE LOSS

WEAK DEPENDENCE ON AREA RATIO

RANGE: 0 TO 5%

EROSION EFFICIENCY

$$I_{SP_D} = I_{SP_{TH}} \ \eta_{CE} \ \eta_{ER} \ \eta_{KIN} \ \eta_{SUB} \ \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\left.\eta_{ER} = \frac{I_{SP_{TD2P}}(\bar{\epsilon})}{I_{SP_{TD2P}}(\epsilon_i)}\right\}$$ from a table of $I_{SP_{TD2P}}$ vs ϵ

$$\epsilon = (r/r^*)^2$$

$$dr^*/dt = \frac{1}{\rho_m} \dot{B}_c' \, G \, C_H$$

Mike D. question came up on $\dot{B}_c'$ defin

NOTES:

BASED ON RATIO OF TIME AVERAGED TO INITIAL EXIT AREA

MATERIALS: CP, 3-D CC,
ATJ, G-90, PYROLYTIC GRAPHITE

RANGE: 0 TO 2%

KINETIC EFFICIENCY

$$I_{SP_D} = I_{SP_{TH}} \, \eta_{CE} \, \eta_{ER} \, \eta_{KIN} \, \eta_{SUB} \, \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\eta_{KIN} = I_{SP_{ODK}} / I_{SP_{RE}}$$

NOTES:

- NO MASS TRANSFER BETWEEN PHASES
- ZERO LAG
- 1D STREAMLINE BUT FLOW IS 2D
- ERROR INCREASES WITH AREA RATIO
- RANGE: .05 TO 10%

SUBMERGENCE EFFICIENCY

$$I_{SP_D} = I_{SP_{TH}} \; \eta_{CE} \; \eta_{ER} \; \eta_{KIN} \; \eta_{SUB} \; \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\eta_{SUB} = 1. - .000684 \left(\frac{P \xi}{A^*} \right) \frac{S^{.4}}{D_t^{.2}}$$

NOTES:

BASED ON LIMITED DATA

EFFORT PARTLY ACCOUNTED BY FCT

RANGE: 0 TO 1%

TWO-DIMENSIONAL AND TWO-PHASE EFFICIENCY

$$I_{SP_D} = I_{SP_{TH}} \, \eta_{CE} \, \eta_{ER} \, \eta_{KIN} \, \eta_{SUB} \, \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\eta_{TD2P} = I_{SP_{TD2P}} / I_{SP_{GPE}} \quad , \quad F_{SP_{TD2P}} = \bar{F}_{IL} + \Delta\bar{F} - \alpha \Delta F_p$$

$$\bar{F}_{IL} = 2\pi \int_0^{r_w} \Big\{ (P + \rho u^2) r\,dr - \rho u v r\,dz + \sum \left(\rho_p u_p^2 r\,dr - \rho_p u_p v_p r\,dz \right) \Big\}$$

$$\Delta F = 2\pi \int_a^b P r\,dr$$

$$\Delta F_p = 2\pi \int_a^b \sum \left\{ \rho_p u_p^2 r\,dr - \rho_p u_p v_p r\,dz \right\}$$

$$0 \le \alpha \le 1 \quad , \quad \alpha \approx .3$$

NOTES:

- CONSTANT GAS PROPERTIES
- SIMPLE PHASE CHANGE MODEL
- ENERGY TRANSFER BETWEEN PHASES
- NO MASS TRANSFER BETWEEN PHASES
- RANGE: 0 TO 8%

Advanced Transonic Program

The Advanced TranSonic (ATS) program determines the subsonic and transonic flow field in a solid propellant rocket motor.

- Unsteady two-dimensional flow
- Steady flow solution at large time
- Coupled gas-particle flow
- Perfect gas
- Constant size particles

The result of the ATS program is a supersonic initial-value downstream of the nozzle geometric throat from which the TD2P analysis can be initiated. A portion of the nozzle submergence loss is included in the results predicted by the ATS program.

BOUNDARY LAYER LOSS

$$I_{SP_D} = I_{SP_{TH}} \, \eta_{CE} \, \eta_{ER} \, \eta_{KIN} \, \eta_{SUB} \, \eta_{TD2P} - \Delta I_{SP_{BL}}$$

$$\Delta I_{SP_{BL}} = \frac{\Delta F_{BL}}{\dot{m}_{TD2P}} + \left(I_{SP_{TD2P}} - I_{SP_{TD2P}}(\epsilon_{BL}) \right)$$ — questioned calculation

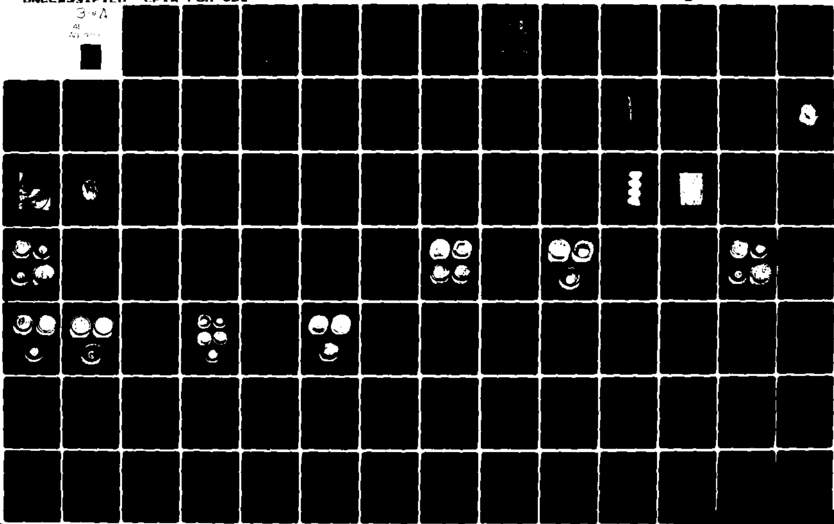
$$\Delta F_{BL} = \left(2\pi r \rho U^2 \theta \cos\alpha \right)_e \left[1 - \frac{\delta^* P}{\theta \rho U^2} \right]_e$$

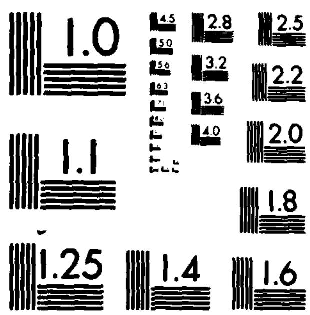
$$\epsilon_{BL} = \left(\frac{r_e - \delta_e^* \cos\alpha}{r^* - \delta_*^*} \right)^2$$

NOTES:

- SAME FORMULA AS IN JANNAF LIQUID PERF. METH.
- TOTAL PRESSURE CORRECTED TO MATCH TD2P — make clear
- NO PARTICLES AT WALL
- EROSION AND ROUGHNESS IGNORED
- RANGE: .5 TO 5%

AD-A089 831 JOHNS HOPKINS UNIV LAUREL MD CHEMICAL PROPULSION INF--ETC F/G 21/8.2
JANNAF PERFORMANCE STANDARDIZATION SUBCOMMITTEE, 13TH MEETING M--ETC(U)
JUL 80 H F HEGE N00024-78-C-5384
UNCLASSIFIED CPIA-PUB-321 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

New Considerations

One-Dimensional Three-Phase Flow Program

OD3P - particle radiation
solidification and crystallization
collisions and agglomeration
fragmentation
nucleation and condensation
vaporization, sublimation, and melting

Replacement of TBL - integral or finite difference method?
mass diffusion?

SPACE MOTOR COMBUSTION

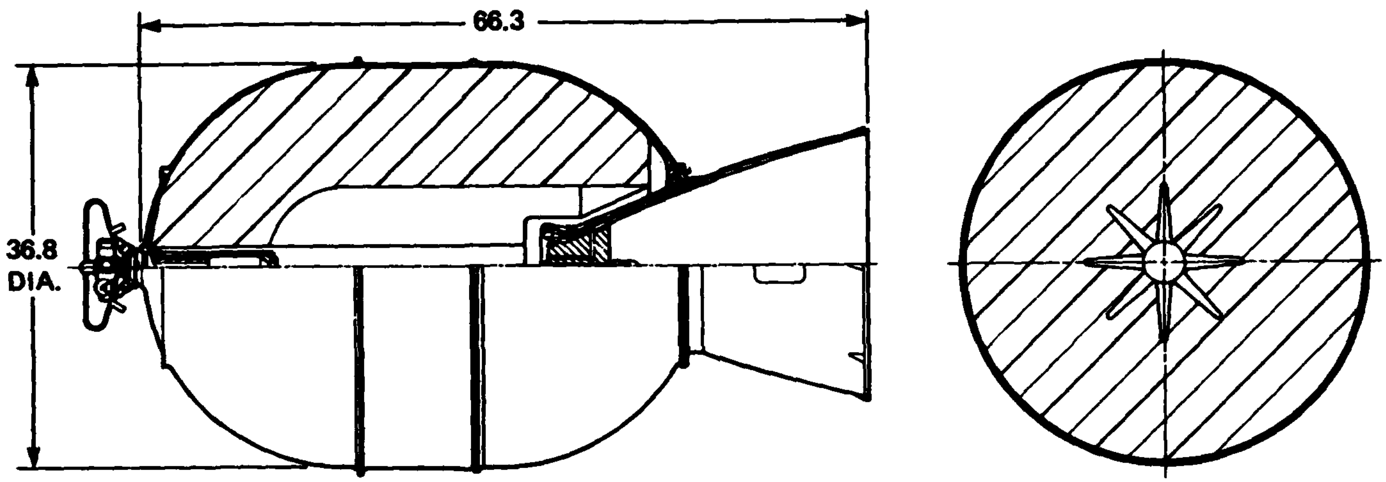
SPIN EFFECTS

W. N. BRUNDIGE
THIOKOL CORPORATION
ELKTON DIVISION

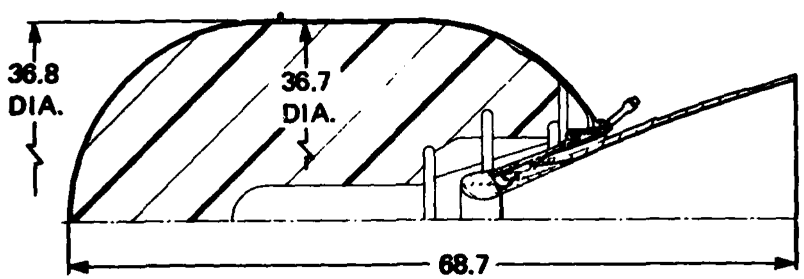
Y280115

Thiokol / ELKTON DIVISION

DESIGN COMPARISON



STAR 37E DELTA THIRD STAGE ROCKET MOTOR



STAR 37X ROCKET MOTOR

SC4903J

Thiokol / ELKTON DIVISION

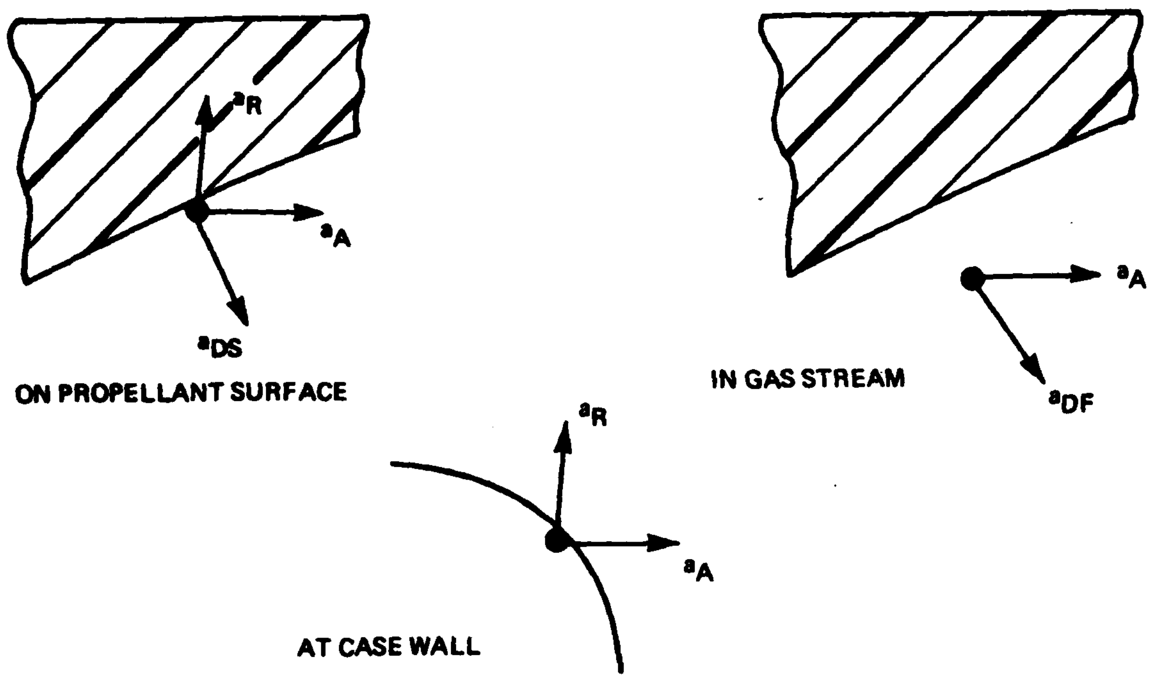
MOTOR ENVIRONMENT

	NOMINAL	EXTREMES
PRESSURE, PSIA	300 – 700	150 – 1200
RADIAL ACCELERATION, G'S	0 – 10	0 – 20
AXIAL ACCELERATION, G'S	2 – 8	0 – 10
BURN RATE, IN./SEC	0.18 – 0.26	0.15 – 0.40

Y1079099

Thiokol / ELKTON DIVISION

ACCELERATION VECTORS ON PARTICLES IN MOTOR



$$\left.\begin{aligned} a_R &= f(r, \Omega^2) \\ a_A &= f(F_t, m_t^{-1}) \end{aligned}\right\} \qquad F_I = f(a_R, a_A, d_{Al}^3, \rho Al)$$

$$a_{DS} = Cf(d_{Al}, r_b, P_c, M_{gs}, T_s, \rho Al)$$

$$a_{DF} = Cf(d_{Al}, r_b, P_c, M_{gF}, T_F, \rho Al)$$

Y1079100

Thiokol / ELKTON DIVISION

MAJOR UNCERTAINTIES CRITICAL TO MOTOR ANALYSIS

- PARTICLE DENSITY
- PARTICLE SIZE DISTRIBUTION
- TEMPERATURE GRADIENT ACROSS PARTICLE ON SURFACE
- EFFECT OF GAS FLOW AND TEMPERATURE AFTER PARTICLE DEPOSITION ON INERT SURFACE
- PARTICLE PROPULSIVITY

Y1079101

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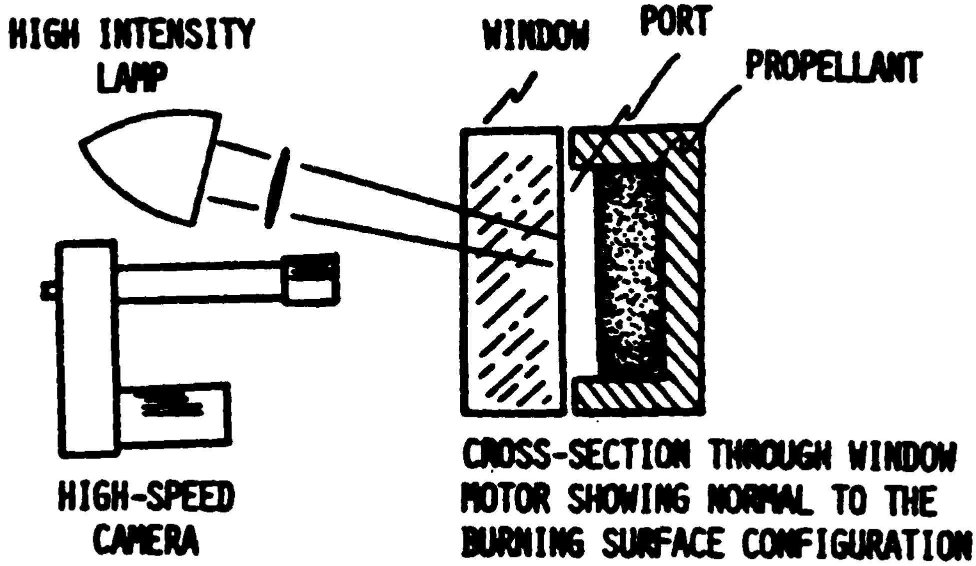
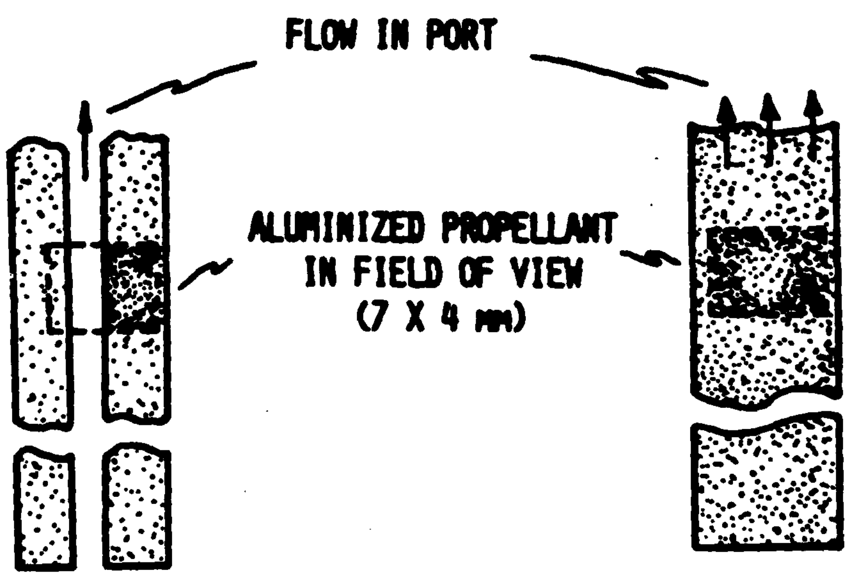
APPARATUS FOR CROSS FLOW PHOTOGRAPHY



A) ARRANGEMENT FOR PHOTOGRAPHING ALUMINIZED PROPELLANT.



B) PROPELLANT CONFIGURATION OF SIDE VIEW PHOTOGRAPHY.

C) PROPELLANT CONFIGURATION FOR NORMAL TO THE BURNING SURFACE PHOTOGRAPHY.

PARTICLE ACCELERATION DUE TO DRAG FORCE

$$a_{Ag} = \frac{F_I}{m} = \frac{0.5\, C_D\, \rho_g (u_g - u_{Ag})^2\ (\pi/4)\, d^2_{Ag}}{(\pi/6)\ \rho_{Ag}\ d_{Ag}{}^3}$$

WHERE

$$C_D = 27/R_e{}^{0.84} \text{ FOR } R_e \leqslant 80$$

AND

$$R_e = \frac{d_{Ag}\,(u_g - u_{Ag})\,\rho_g}{\mu_g}$$

THEREFORE

$$a_{Ag} \cong \frac{(u_g - u_{Ag})^{1.16}}{d_{Ag}{}^{1.84}}$$

Y280116

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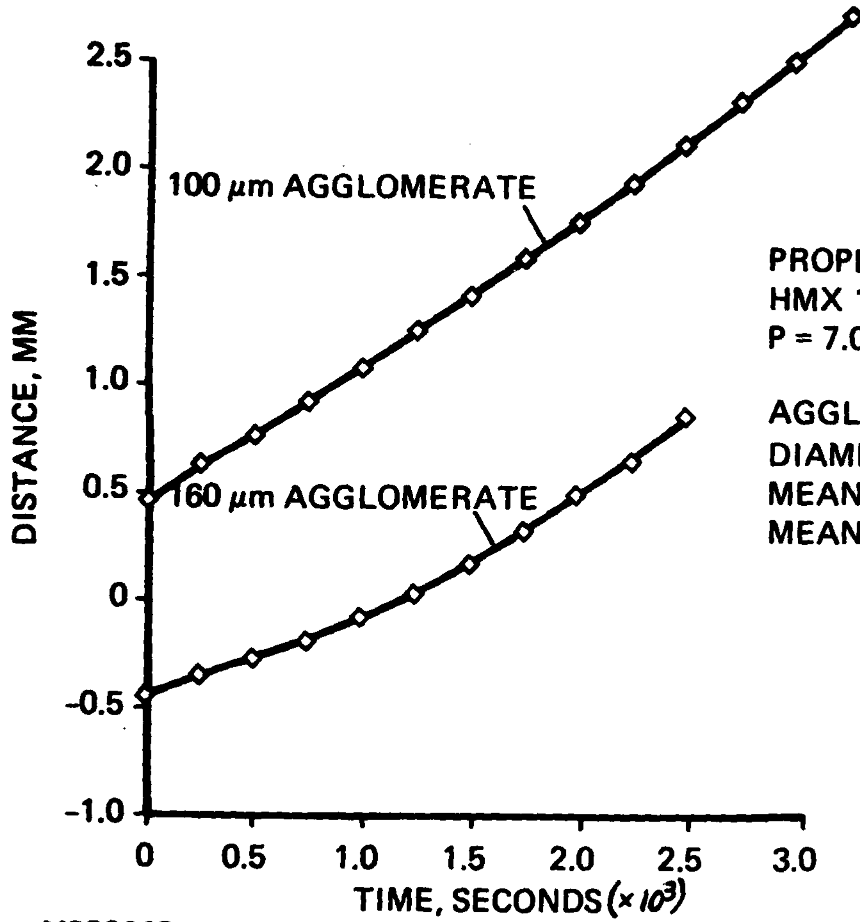
PARTICLE DISPLACEMENT VS TIME



PROPELLANT 1780-50
HMX 12%/AP 57%/Al 21%/HTPB 10%
$P = 7.0$ MPa, $V_{CROSSFLOW} \sim 2$ m/s

AGGLOMERATE:

DIAMETER, μm	160	100
MEAN VELOCITY, m/s	0.51	0.69
MEAN ACCELERATION, m/s^2	213	71

Y280118

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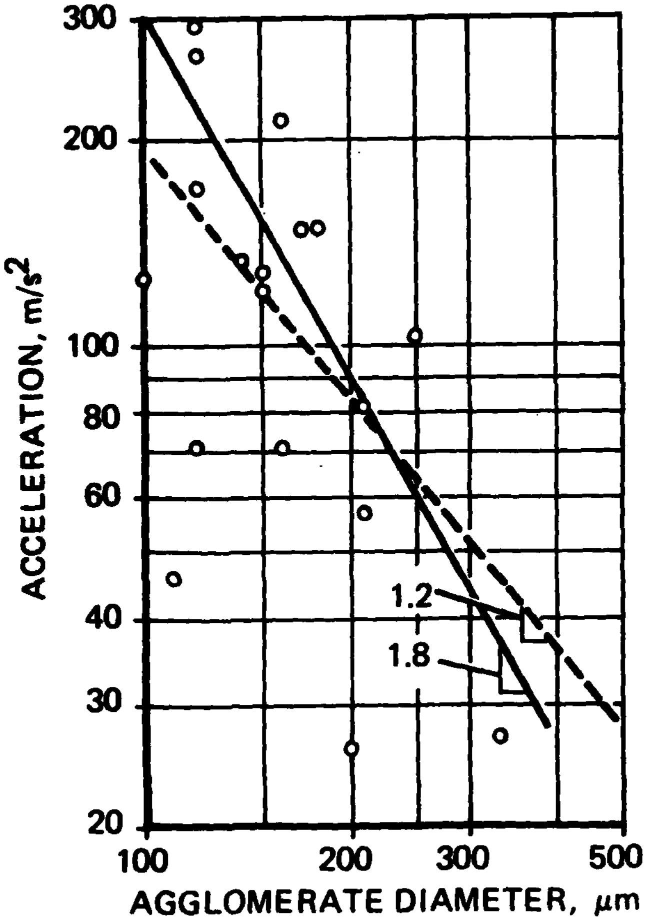
PARTICLE ACCELERATION VS SIZE



PROPELLANT 1780-50
HMX 12%/AP 57%/Al 21%/HTPB 10%
P = 7.0 MPa, $V_{CROSSFLOW}$ ~2 m/s

Y280117

Thiokol/ELKTON DIVISION

EXPENDED INERTS
AND
SLAG PERFORMANCE PROCEDURE

J. T. LAMBERTY

UT-CSD SUNNYVALE, CA

I

Proposed Definitions

Propellant I_{sp}	$\dfrac{\text{Impulse Attributed to Propellant}}{\text{Propellant Weight Expended}}$	I_{sp_p}	$\dfrac{I_t}{W_p} - \dfrac{W_{inert}}{W_p} \times I_{sp_{inert}}$
Delivered I_{sp}	$\dfrac{\text{Total Delivered Impulse}}{\text{Propellant Weight Expended}}$	I_{sp_d}	$\dfrac{I_t}{W_p}$
Effective I_{sp}	$\dfrac{\text{Total Delivered Impulse}}{\text{Total Expended Weight}}$	$I_{sp_{eff}}$	$\dfrac{I_t}{W_p + W_{inerts}}$

$$I_t = \int F dt$$

CPIA PUBLICATION NO. 80 DEFINITIONS

SYMBOL	NAME	DEFINITION
I_{sp}	Propellant specific impulse	This symbol is used only in (1) general reference to propellant specific impulse, or (2) reporting non-standard corrected values of I_{spd}. All numerical values must be accompanied by specification of the following assumptions: (P_c, P_{amb}, α, ϵ). Use the same time interval propellant mass assumptions as for I_{spd}; therefore do not report a numerical value of I_{sp} without also reporting the corresponding value of I_{spd}.
I_{spd}	Measured (delivered) propellant specific impulse	Calculated from data from an actual motor firing. All numerical values must be accompanied by specification of the following motor conditions. a) Chamber pressure b) Ambient pressure c) Nozzle area expansion ratio d) Nozzle divergence half-angle e) Time interval used for impulse determination f) Propellant mass assumption

Motor No.	Mfg.	Mfg. No.	Binder	% AP	% Al	Type Insulation	% Inerts	$\bar{P}c$	$\bar{\epsilon}$	I_{sp} Inerts	Δ I_{sp} Inerts	Del. I_{sp}	Prop. I_{sp}
1	ASPC	SVM-1	CTPB	73	15	(1)	1.56	377	33.3	189	2.94	288.3	285.4
2		SVM-2	CTPB	73	15	(1)	1.05	322	28.0	194	2.03	284.0	282.0
3		SVM-4A	CTPB	73	15	(1)	1.31	731	40.0	177	2.32	289.7	287.4
4		SVM-5	CTPB	73	15	(1)	1.19	515	26.8	181	2.15	281.2	279.0
5		SVM-6	CTPB	73	15	(1)	1.40	602	54.0	176	2.46	293.2	290.7
6		SVM-7	CTPB	73	15	(2)	.68	612	51.2	216	1.46	293.6	292.1
7		MM III St. 2	CTPB	73	15	(1)	.69	443	24.8	205	1.41	287.6	286.1
8		MM III, St. 3	CTPB	73	15	(1)	.87	507	23.6	191	1.66	284.7	283.0
9		MM III, St. 3	CTPB	73	15	(1)	.87	507	42.7	236	2.05	293.0	290.9
10		MM III, St. 3	CTPB	73	15	(1)	.87	523	87.9	247	2.15	300.3	298.2
11	UT-CSD	FW-4	PBAN	68	16.4	(1)	.52	683	47.3	142	.74	286.2	285.4
12		FW-5	PBAN	68	16.4	(1)	.84	670	55.6	138	1.15	286.5	285.3
13		FW-5A	PBAN	68	16.4	(1)	.71	733	96.9	127	.90	293.1	297.1
14		IUS (Large)	HTPB	68	18	(6)	.33	549	33.1	130	.43	287.7	287.2
15	THI	364-3	CTPB	70	16	(3)	.85	568	51.2	141	1.19	290.7	289.5
16		364-4	CTPB	70	16	(3)	.76	545	29.8	138	1.05	284.6	283.5
17		364-11	CTPB	72	16	(3)	.82	547	32.1	178	1.46	289.5	288.0
19		442-1	CTPB	69	16	(4)	.49	588	39.3	136	.66	272.8	272.1
20		479	CTPB	70	16	(4)	1.37	788	55.0	136	1.86	290.0	288.1
21		521	CTPB	70	16	(4)	1.21	645	50.7	144	1.74	288.6	286.9
22		604	CTPB	70	16	(4)	1.32	485	35.4	137	1.80	285.9	284.1
23		616	CTPB	72	16	(4)	.98	465	460	132	1.29	290.2	288.9
24		640	CTPB	70	16	(4)	.47	676	47.0	147	.69	288.3	287.6
25		714-1	HTPB	71	18	(5)	.47	609	54.6	193	.90	296.8	295.9
26		714-2	HTPB	59	20	(5)	.44	723	74.7	216	.95	298.1	297.1
27	LPC	Y41-4	PBAA	69	16	(4)	2.3	367	40.2	135	3.1	282.7	279.6
28		Y41-7	PBAA	69	16	(4)	2.3	356	149.3	121	2.78	294.3	291.5
29	HERC	258-E6	DB	7	19	(4)	.80	454	25.1	218	1.75	281.7	280.0
30		259-A6	DB	7	19	(4)	.98	344	17.9	216	2.12	281.4	279.3

(1) Silica loaded Buna-N (V45); (2) EPDM (IEM 120); (3) Asb, filled Polyisoprene; (4) Asbestos filled Buna-N; (5) Silica filled EPDM; (6) Silica-asbestos loaded EPDM

INGREDIENT	FORMULA	HEAT OF FORMATION, CAL/MOLE
EPDM	$C_{7.134}\ H_{14.196}$	-44160
BUNA-N	$C_{7.595}\ H_{10.516}\ N_{.584}$	15422
SILICA	$S_{i}O_{2}$	-217800
ASBESTOS	$M_{g}\ S_{i}\ O_{3}$	-357900

TYPE INSULATION	PERCENTAGES USED
SILICA LOADED BUNA-N	31% SILICA, 69% BUNA-N
ASBESTOS FILLED BUNA-N	14% SILICA; 21% ASBESTOS; 65% BUNA-N
SILICA FILLED EPDM	31% SILICA; 69% EPDM
SILICA-ASBESTOS LOADED EPDM	14% SILICA; 21% ASBESTOS; 65% BUNA-N

CASE INSULATION AND NOZZLE INERTS COMPARISON

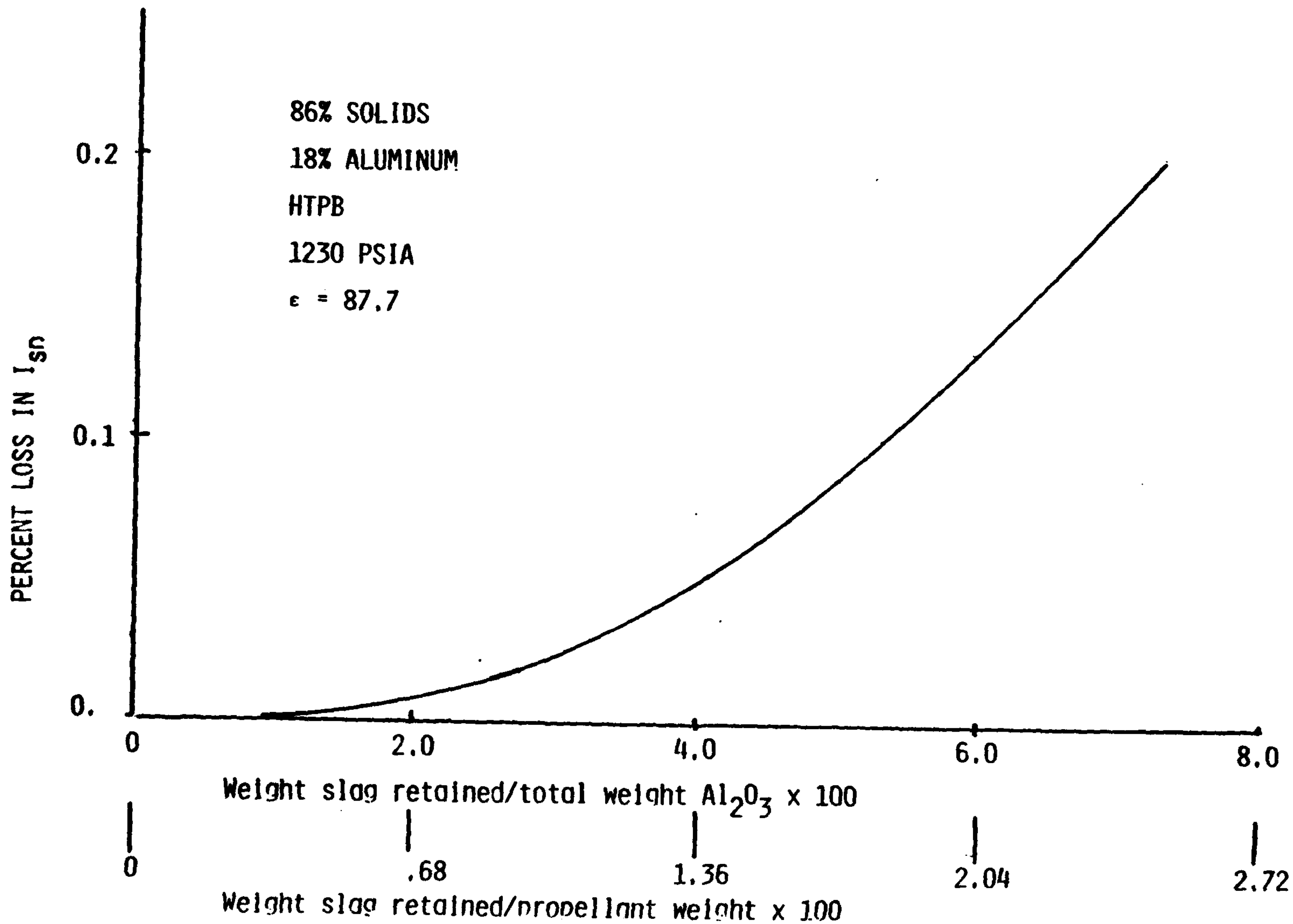
			INERTS I_{sp}		
MOTOR	% TOTAL* INERTS	% NOZZLE* INERTS	TOTAL INERTS AT CHAMBER CONDITIONS	NOZZLE INERTS EXCLUDED	INERTS FROM INSULATION AND NOZZLE
SVM-2	1.05	.35	194	195	184
SVM-4a	1.31	.42	177	180	170
SVM-5	1.19	.43	181	192	182
SVM-6	1.40	.67	176	192	163
SVM-7	.68	.28	216	220	202
MM III, ST 2	.69	.43	205	230	190
MM III, ST 3	.87	.41	191	197	179

* $\frac{\text{INERT WEIGHT}}{\text{PROPELLANT WEIGHT}} \times 100$

CORRELATION RESULTS

EQUATION	X	Y	A	B	R^2	REMARKS
$Y = A + BX$	DEL. I_{sp}	PRED. I_{sp}	-60.1	1.211	.8892	
$Y = A + BX$	PROP. I_{sp}	PRED. I_{sp}	-58.1	1.211	.8961	
$Y = AX^B$	D_t	DEL. I_{sp} EFFICIENCY	.894	.023	.52	16% Al MOTORS
$Y = AX^B$	D_t	PROP. I_{sp} EFFICIENCY	.889	.0244	.59	16% Al MOTORS

I_{sp} LOSS VS SLAG RETENTION



BURNING ANOMALY RATE FACTOR

T. J. KIRSCHNER, JR.
THIOKOL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

Y180045

Thiokol / ELKTON DIVISION

INTRODUCTION

• PREDICTION BASES	TEST MOTOR BURN RATE PROPELLANT PARAMETERS THROAT PARAMETERS THEORETICAL SURFACE AREAS
• MEASURED DEVIATES FROM PREDICTED	
• CORRECTIONS TO PREDICTION	THROAT AREA HISTORY MOTOR C* MOTOR BURN RATE (SCALE FACTOR)

- MEASURED STILL DEVIATES FROM CORRECTED PREDICTION
  BARF, HUMP EFFECT, MOUND EFFECT, ETC

CAUSES

WHAT: DEVIATION OF ACTUAL SURFACE AREA OR BURN RATE ($A_s \, r_b \, \rho = \dot{M} = \frac{G}{C^*} P_c A_t$)

POSSIBLE CAUSES:

- RATE DISTRIBUTION ACROSS WEB
- DEFORMED VS INITIAL GEOMETRY
- BACKSIDE HEAT TRANSFER (BOOTS)
- STRAIN AFFECTED RATE

MAJOR CAUSE IS RATE DISTRIBUTION ACROSS WEB

PROBABLY CAUSED BY PROPELLANT FLOW DURING CASTING

Y180047

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MOTOR TYPES SHOWING RATE/WEB DISTRIBUTIONS

- CP TEST MOTORS
- END BURNERS
- HEAD-END WEB DESIGNS
- STAR DESIGNS

Y180048

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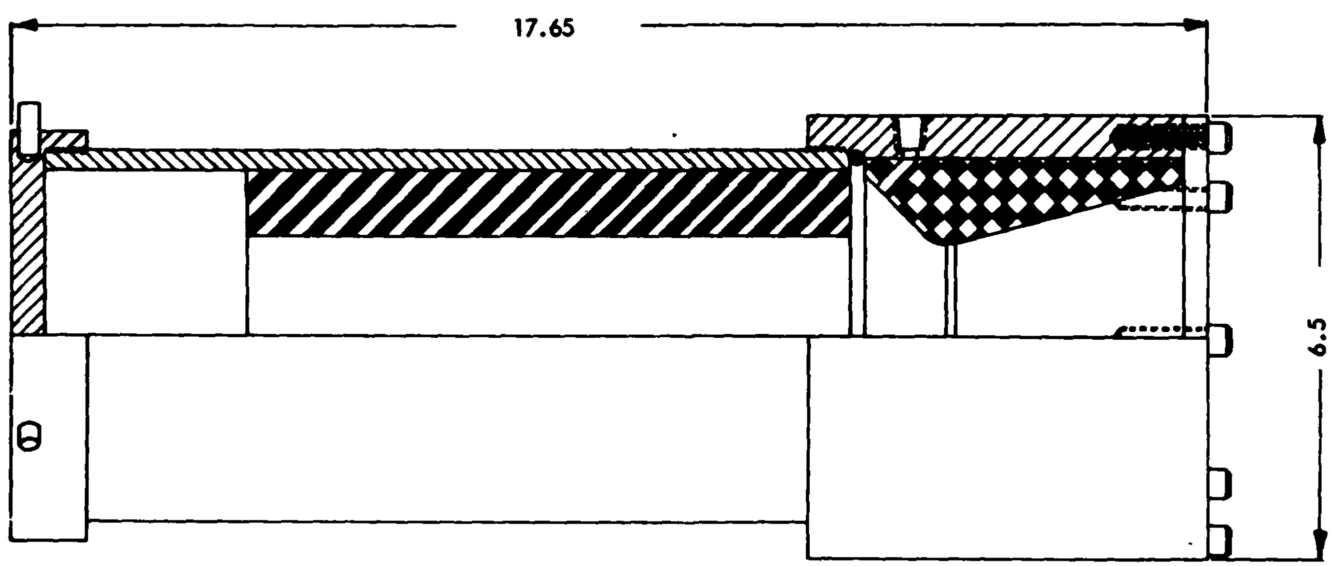
TYPICAL TEST MOTOR



BB6972

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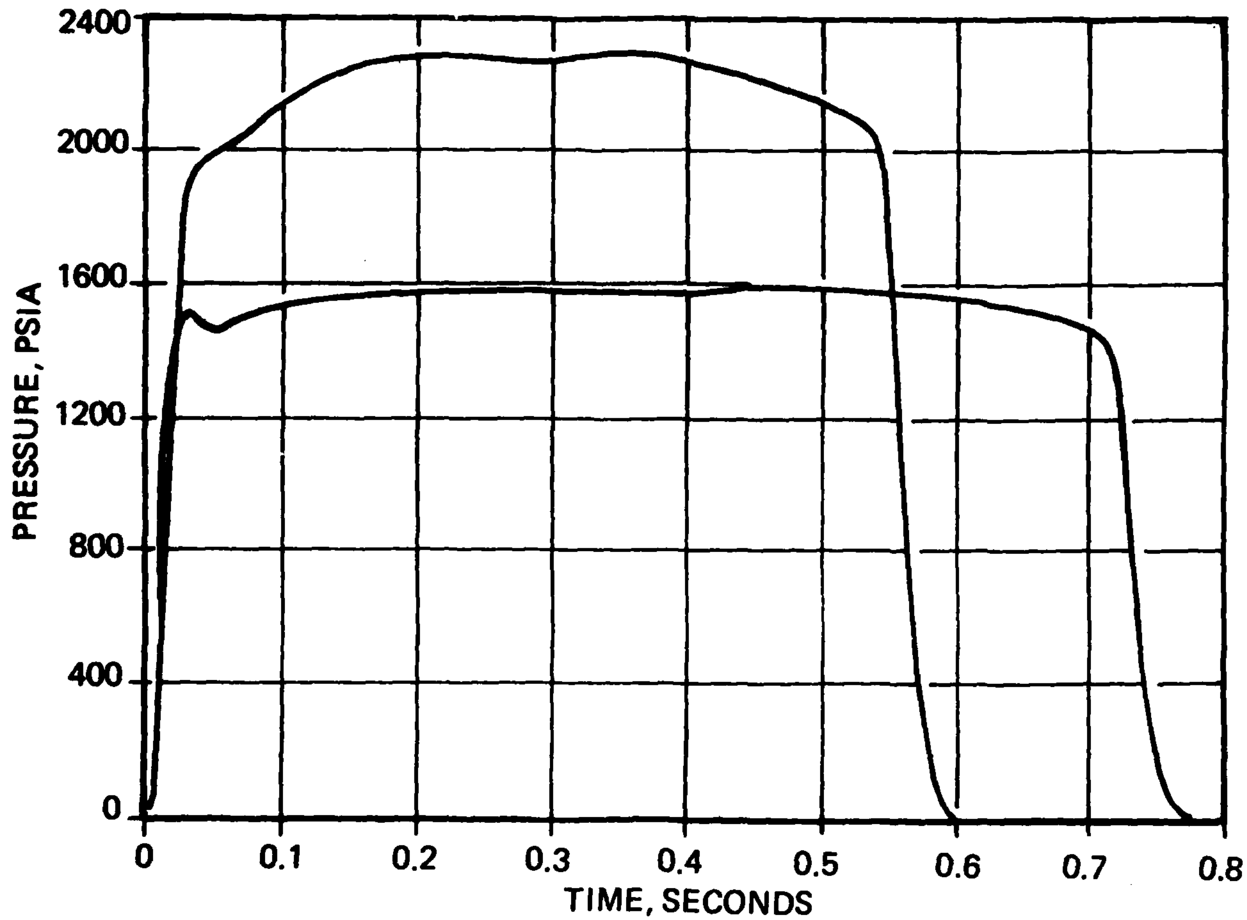
TYPICAL TEST MOTOR P_C VS TIME



SA 6939

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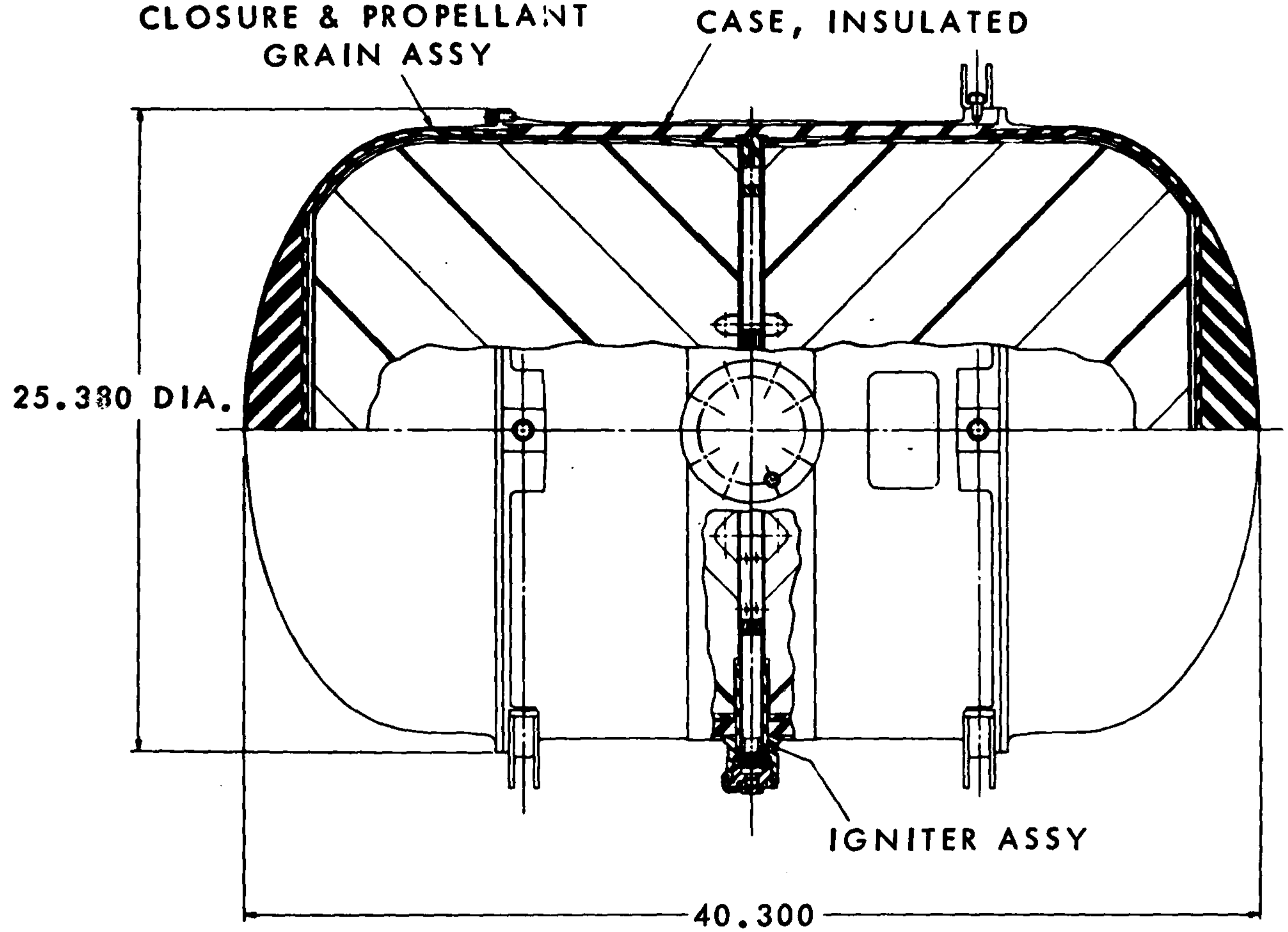
END BURNING GAS GENERATOR



Y468051

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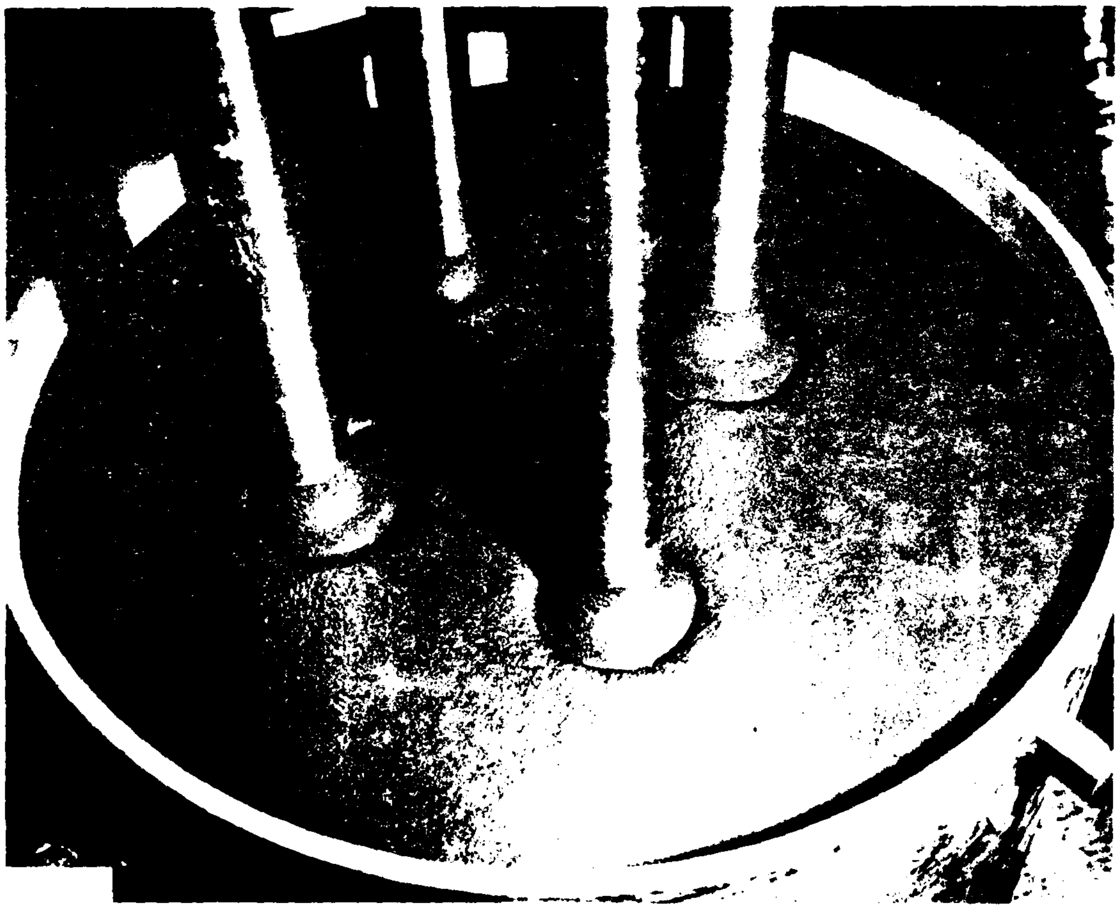
TERMINATED FOUR-BAYONET GRAIN

P767005

Thiokol / ELKTON DIVISION

GRAIN CASTING – FOUR BAYONETS



P767461

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TERMINATED EIGHT SUBMERGED BAYONET GRAIN

P127093

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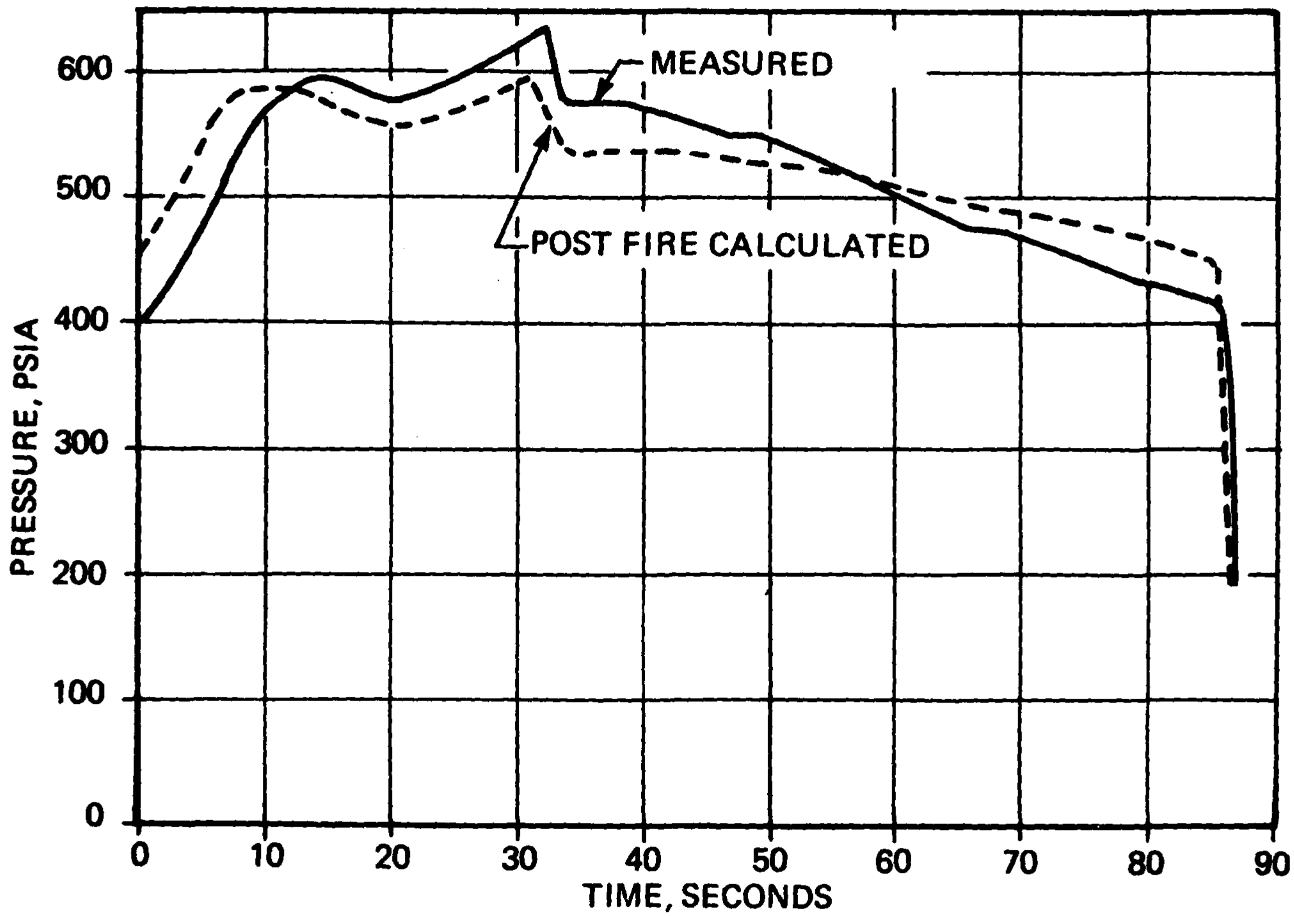
STAR 48 PRESSURE VS TIME



SA 6940

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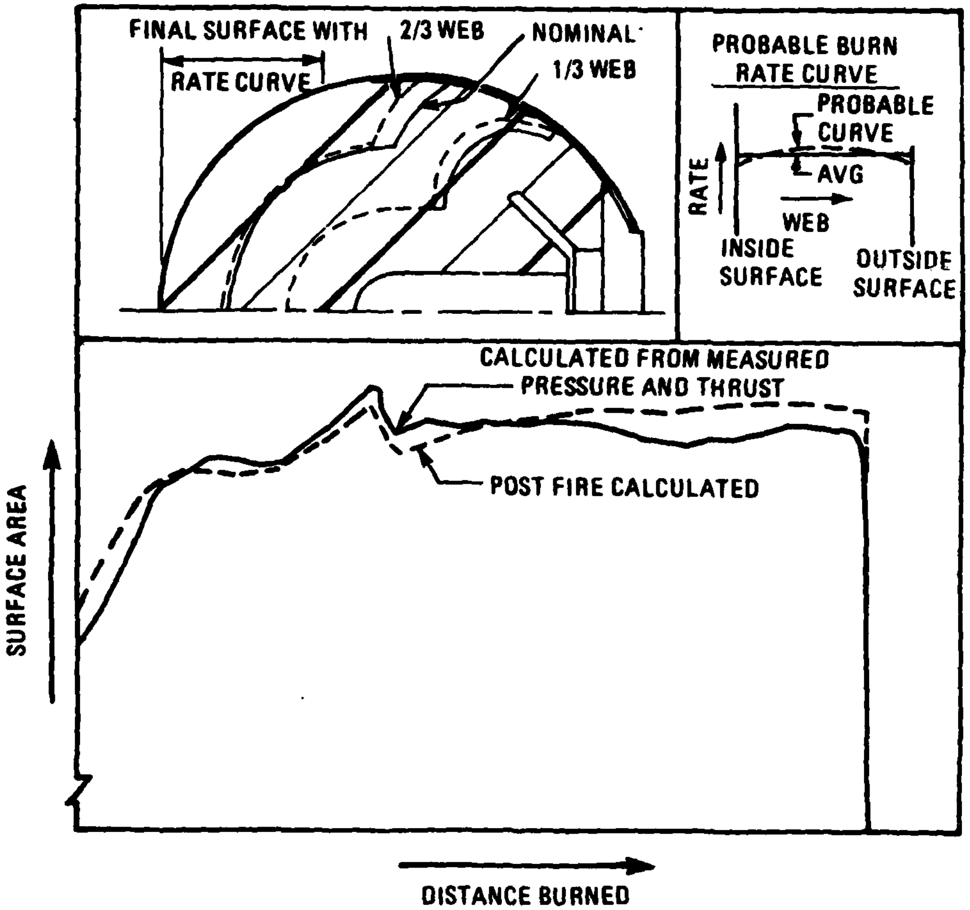
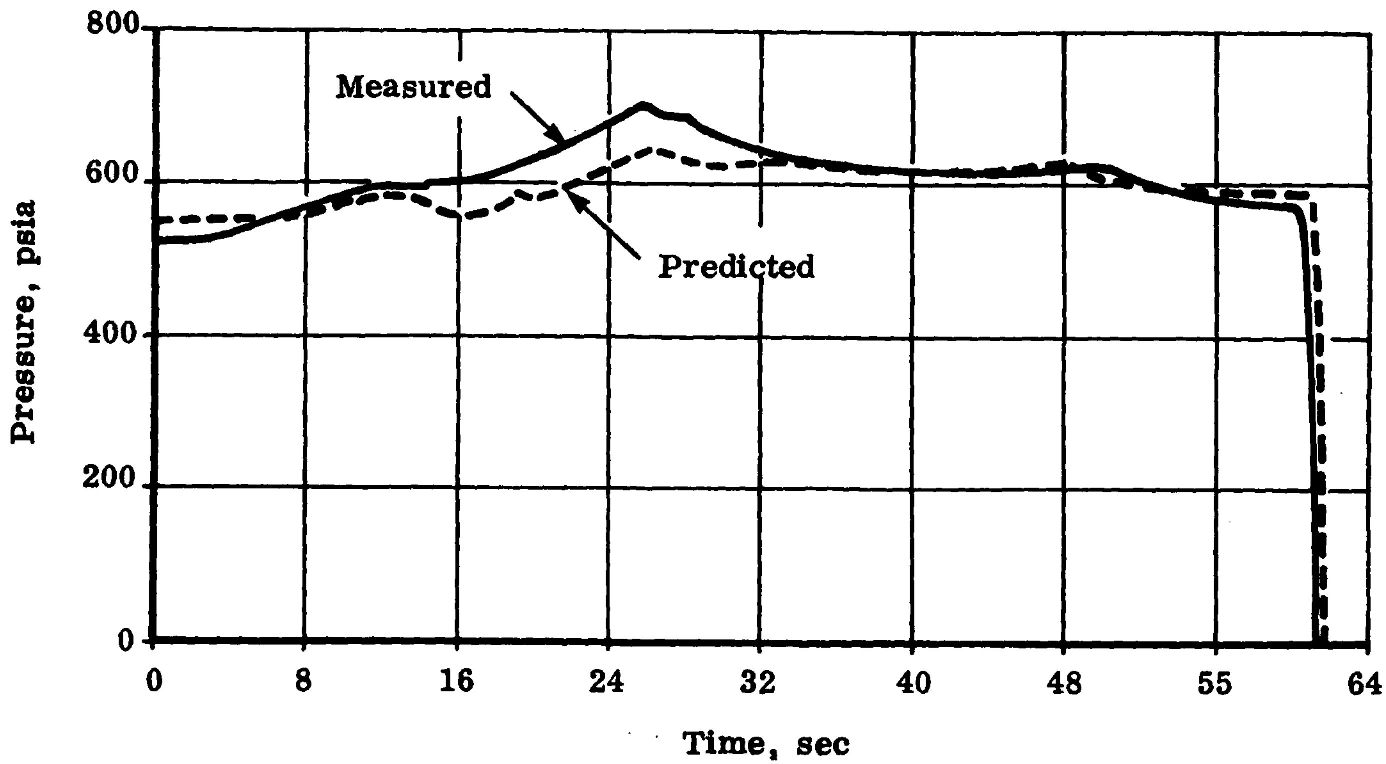
STAR 48 BACKFIT RESULTS



Y279091

Thiokol / ELKTON DIVISION

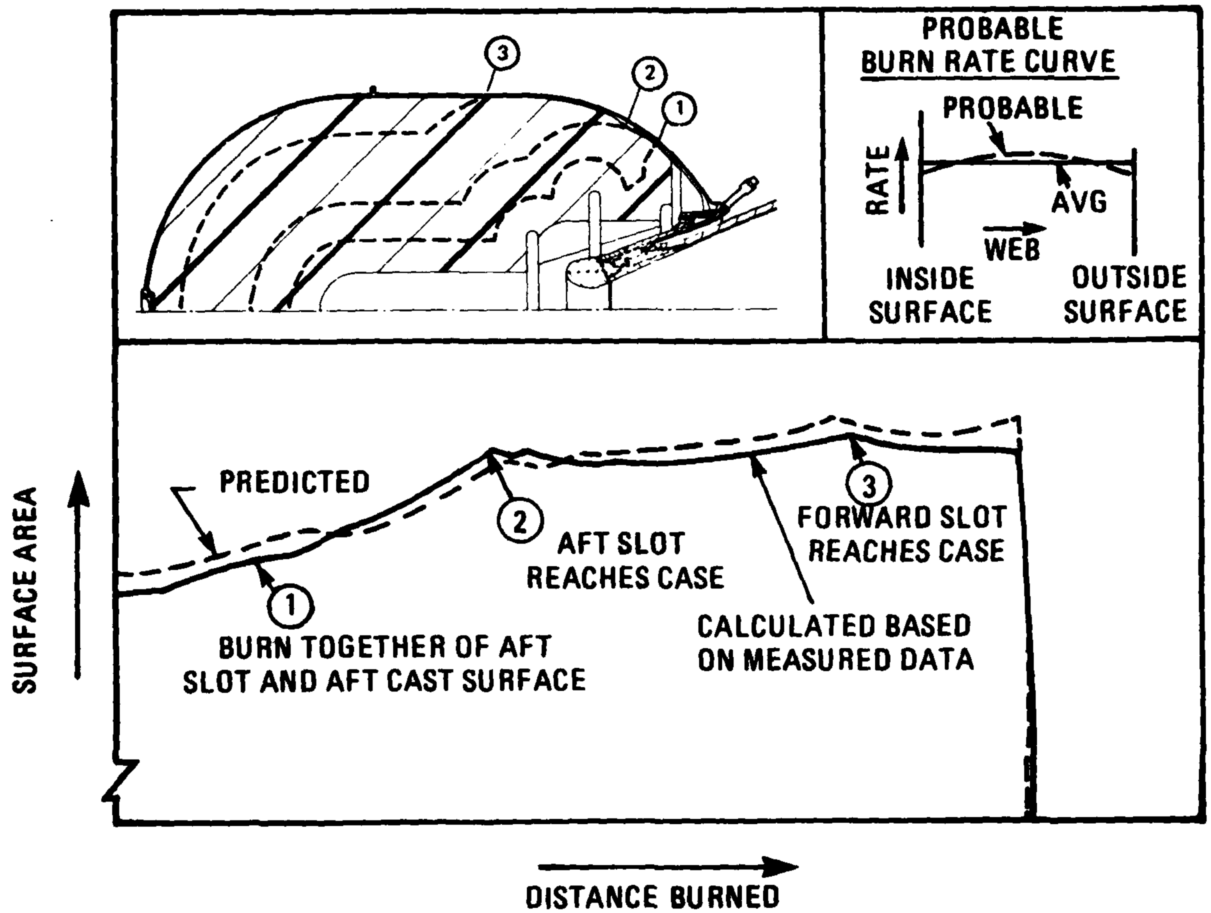
STAR 37X PRESSURE VS TIME



SA5427

Thiokol / ELKTON DIVISION

STAR 37X BACKFIT RESULTS

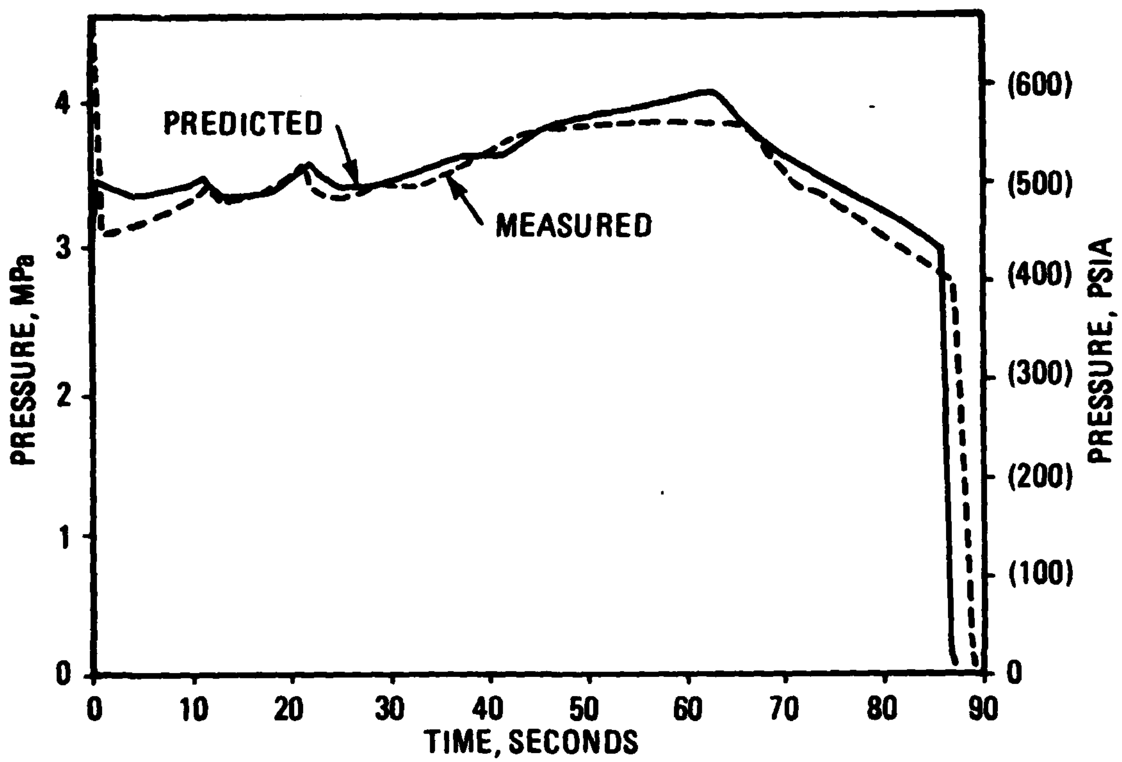


Y279092

Thiokol / ELKTON DIVISION

STAR 48 PRESSURE VS TIME

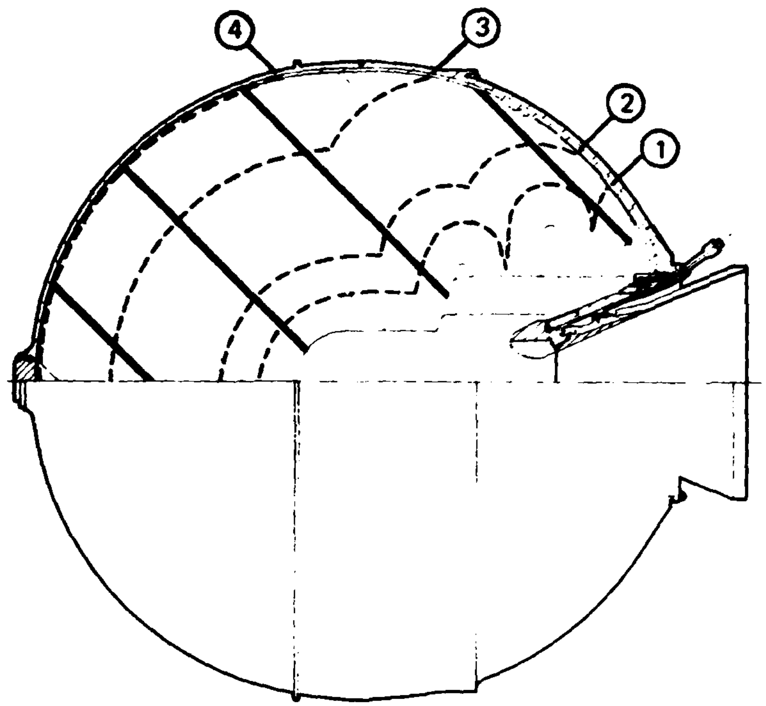
PROPELLANT WT	1656 KG (3650 LB)
WEB FRACTION	84%
SPUN AT 105 RPM	
SEA LEVEL TEST	



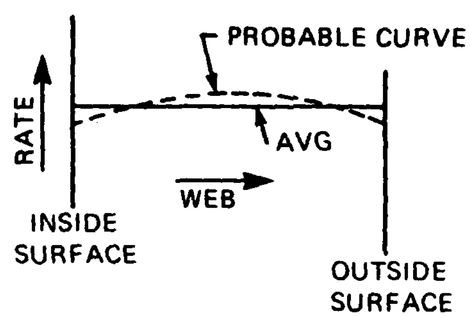
Y279088

Thiokol / ELKTON DIVISION

STAR 48 BURNING PROFILE



PROBABLE BURN RATE CURVE



SC5043A

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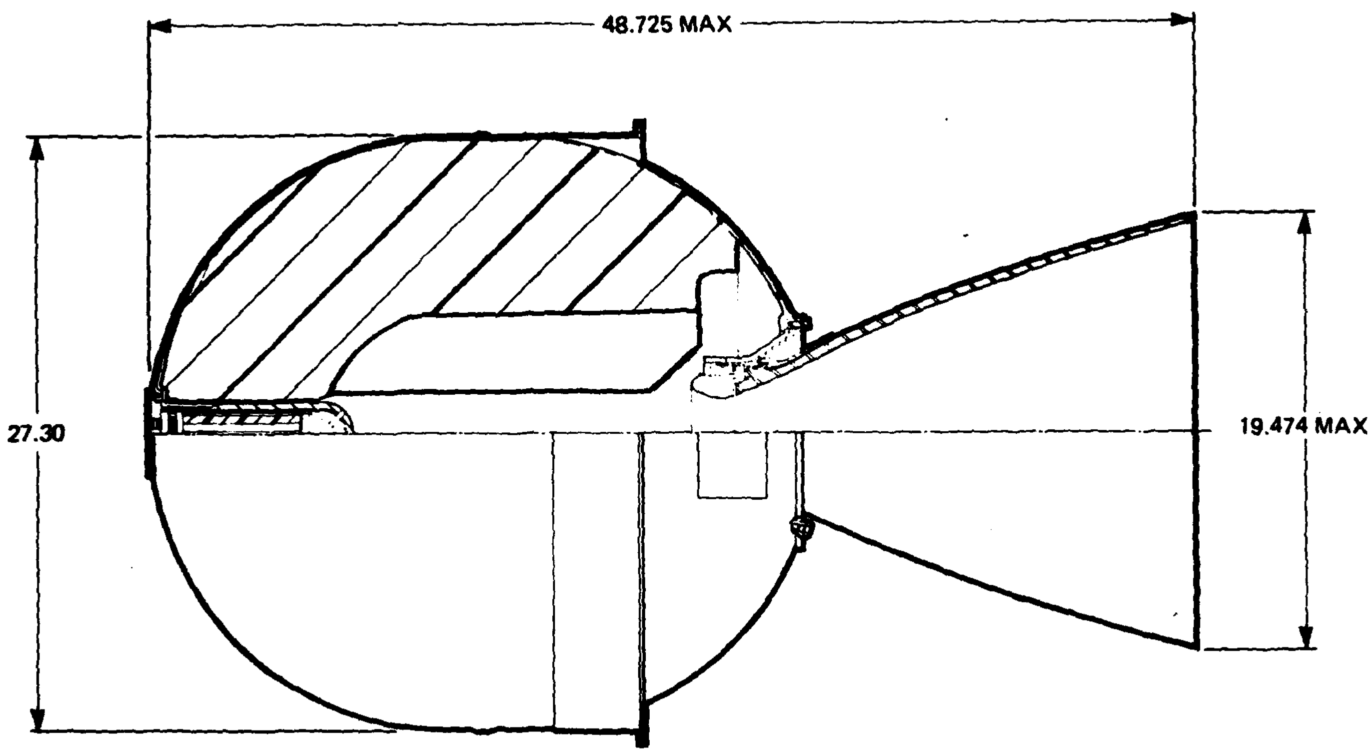
STAR DESIGN MOTOR



Typical Offloaded Motor Configuration

SA6968

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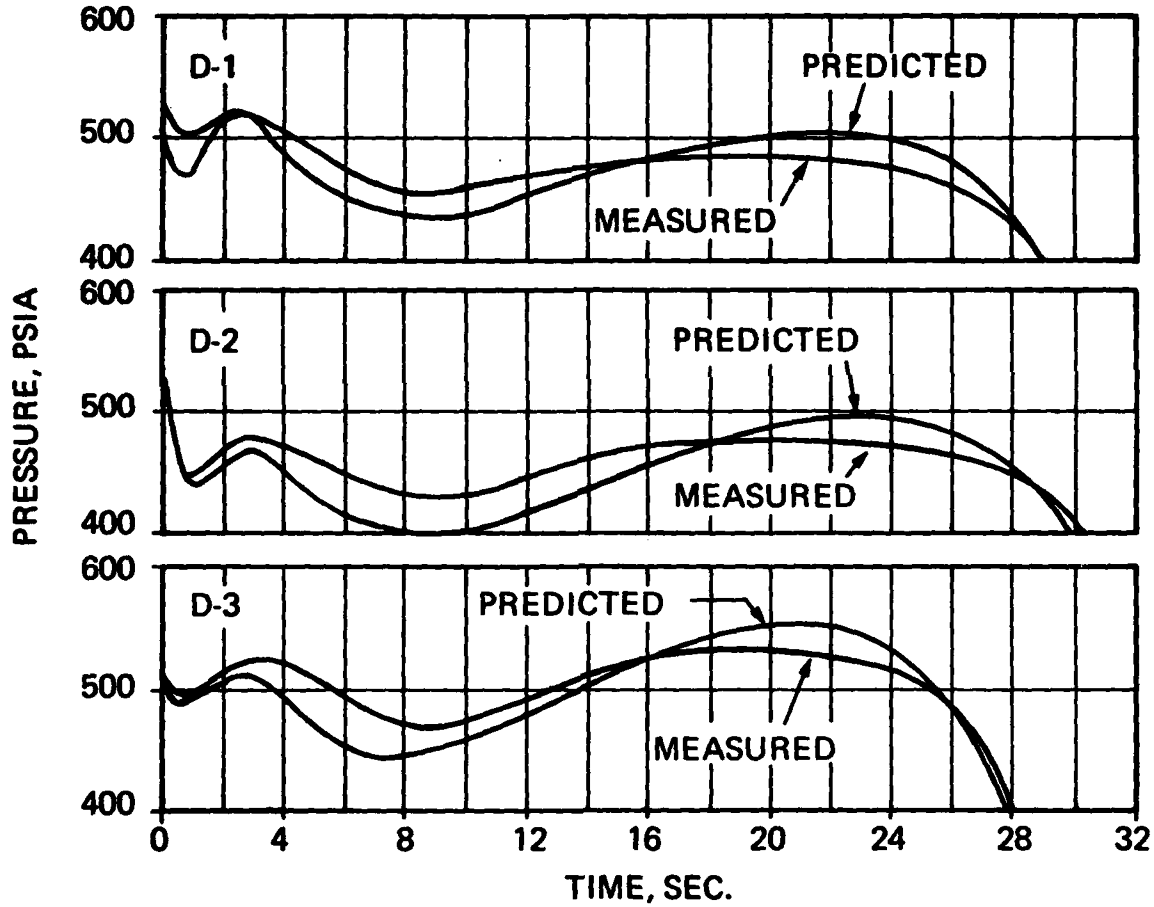
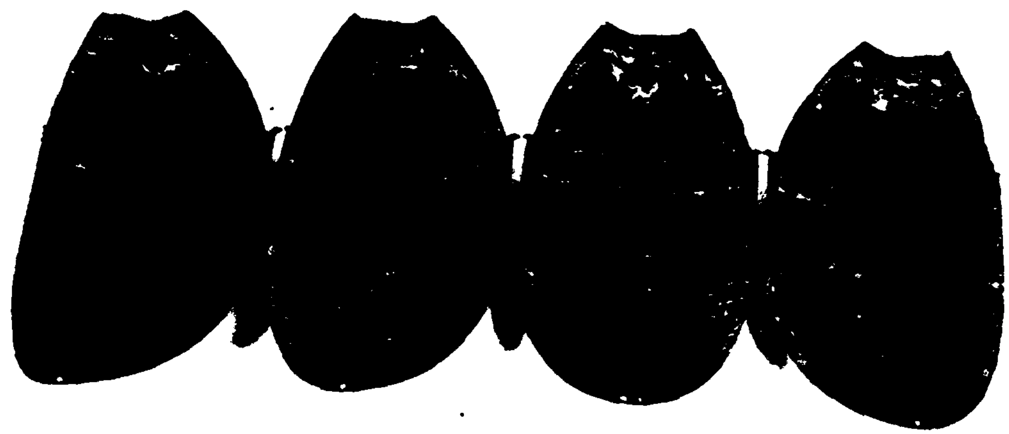
MOTOR P_C VERSUS T FOR DEVELOPMENT MOTORS



Y472105

Thiokol CHEMICAL CORPORATION • ELKTON DIVISION

VIEW OF SECTIONED CASE

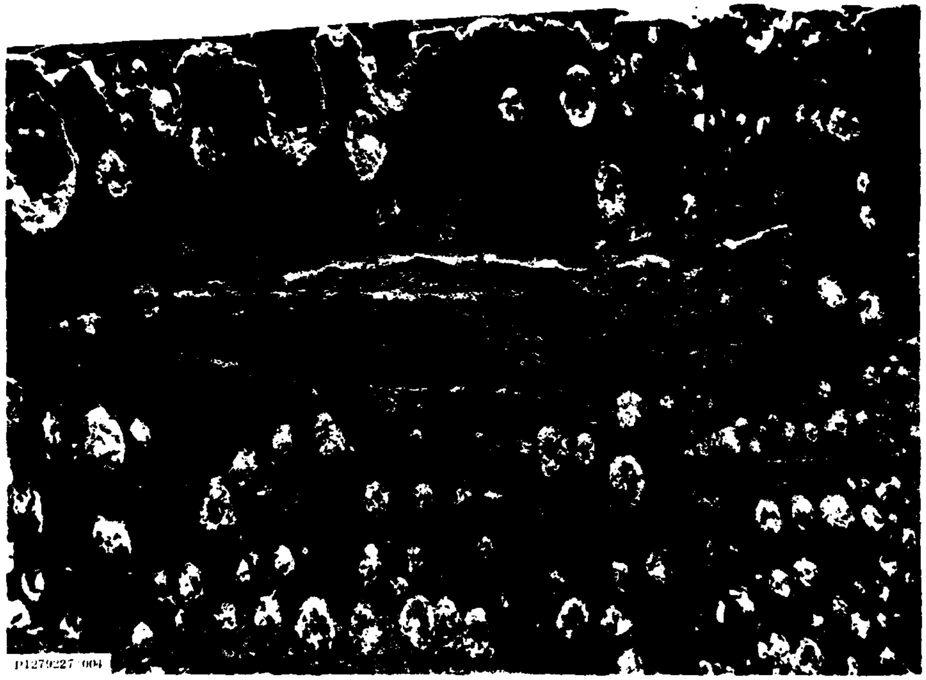


P1279227/001

P1279227/001

Thiokol / ELKTON DIVISION

CLOSEUP OF SLIVER



P1279227/004

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Appendix 17: Particle Impingement Modelling - Performance Effects

PARTICLE IMPINGEMENT MODELLING

PERFORMANCE EFFECTS

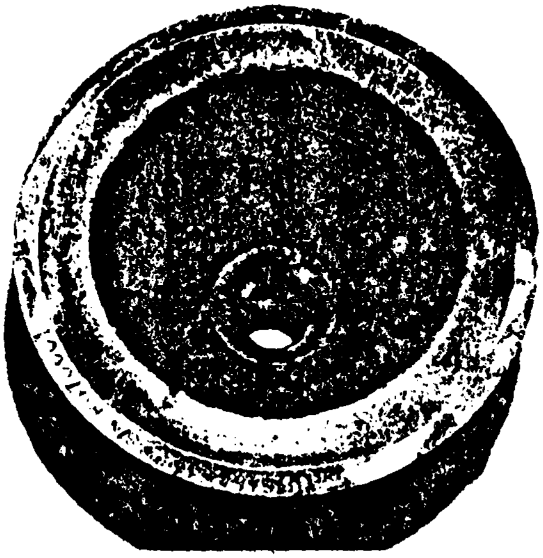
FEBRUARY 1980

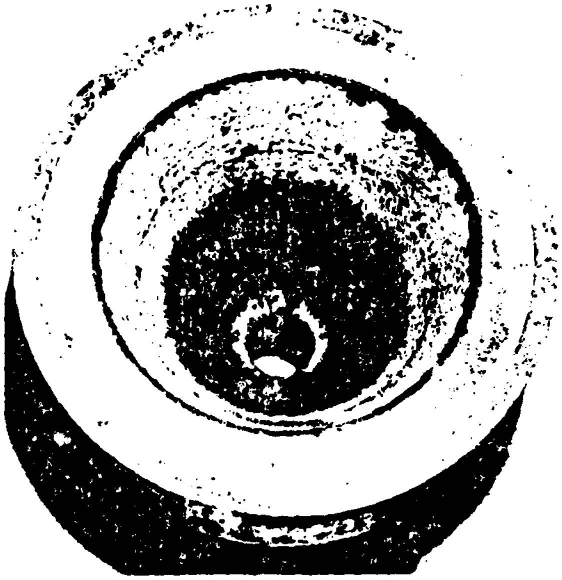
WELDON L. DAINES

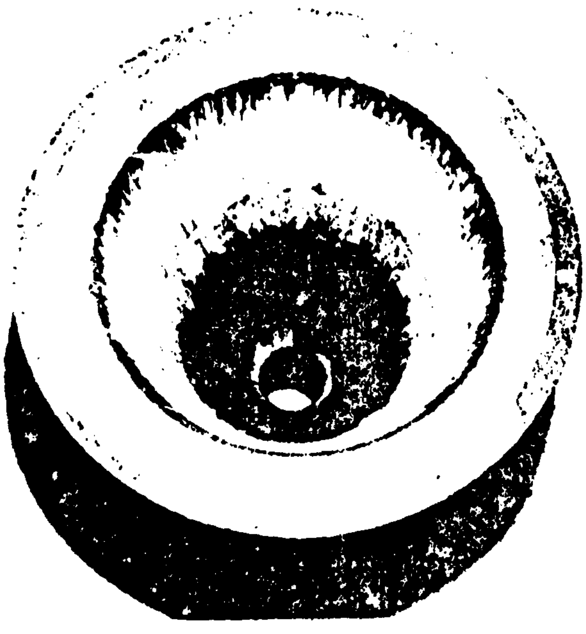
PARTICLE IMPINGEMENT

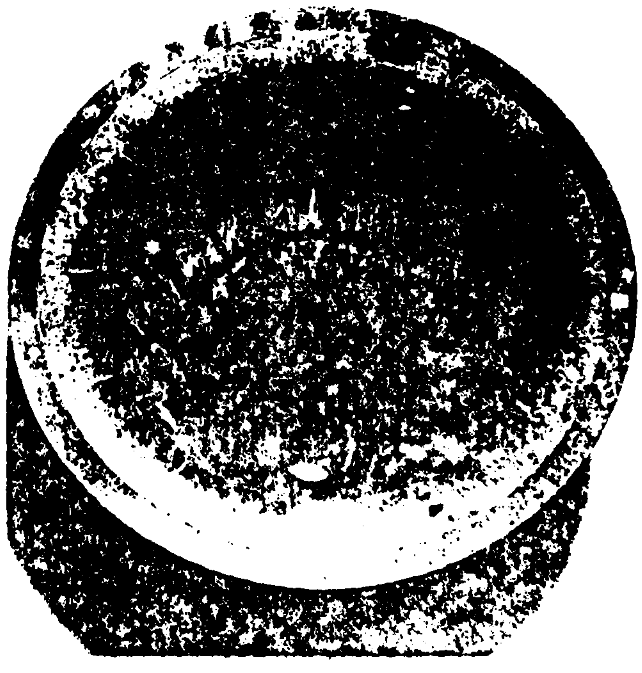
- NOZZLES ARE CONTOURED TO GIVE MAXIMUM EXPANSION IN MINIMUM LENGTH
- EXHAUST GAS TURNS TO FOLLOW THE CONTOUR
- PARTICLES LAG GAS IN BOTH VELOCITY AND DIRECTION
- PARTICLES ARE NOT TURNED QUICKLY ENOUGH AND IMPINGE ON NOZZLE

PARTICLE IMPINGEMENT EFFECTS





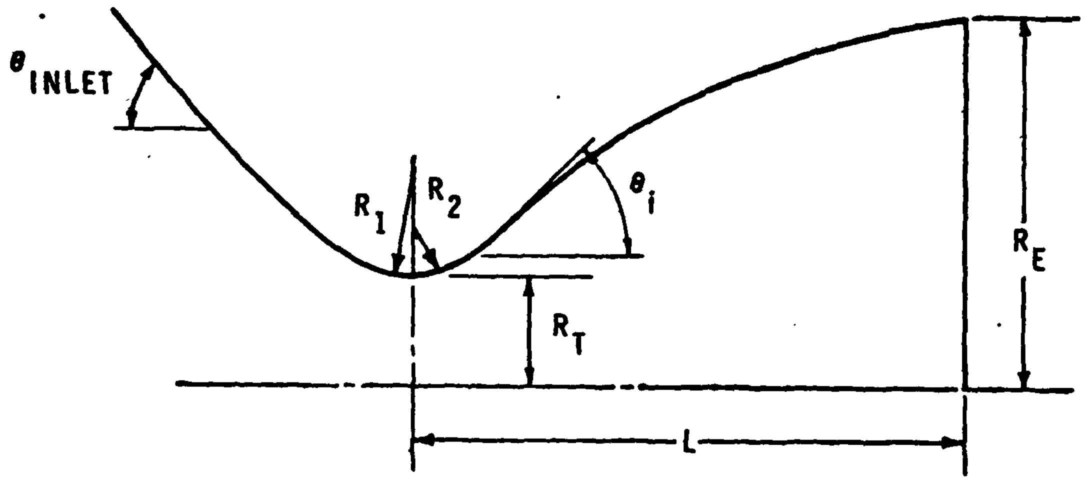




C 4
HERCULES Thiokol

NOZZLE PARAMETERS

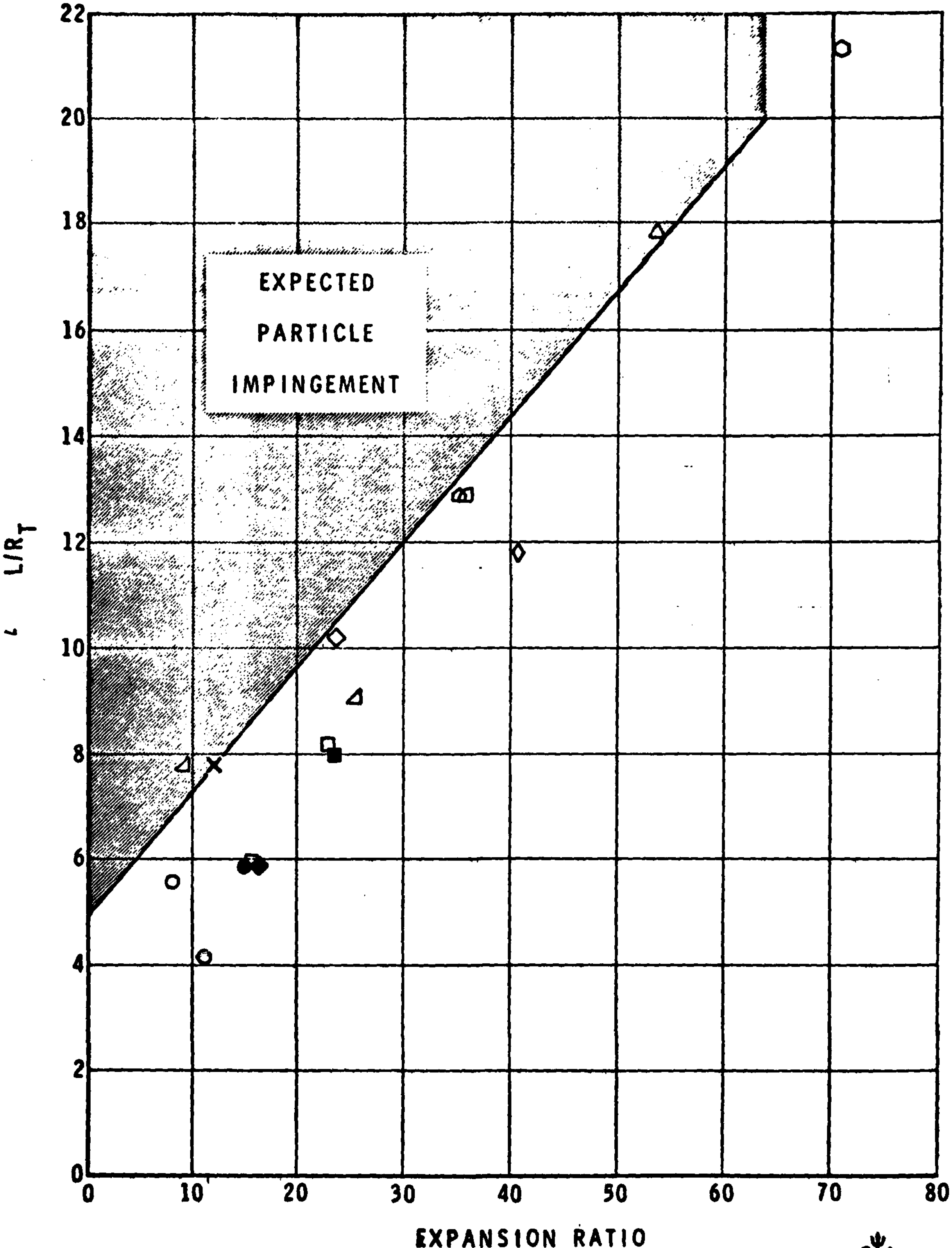
$$\frac{A}{A} = \text{EXPANSION RATIO} = \left(\frac{R_E}{R_T}\right)^2$$



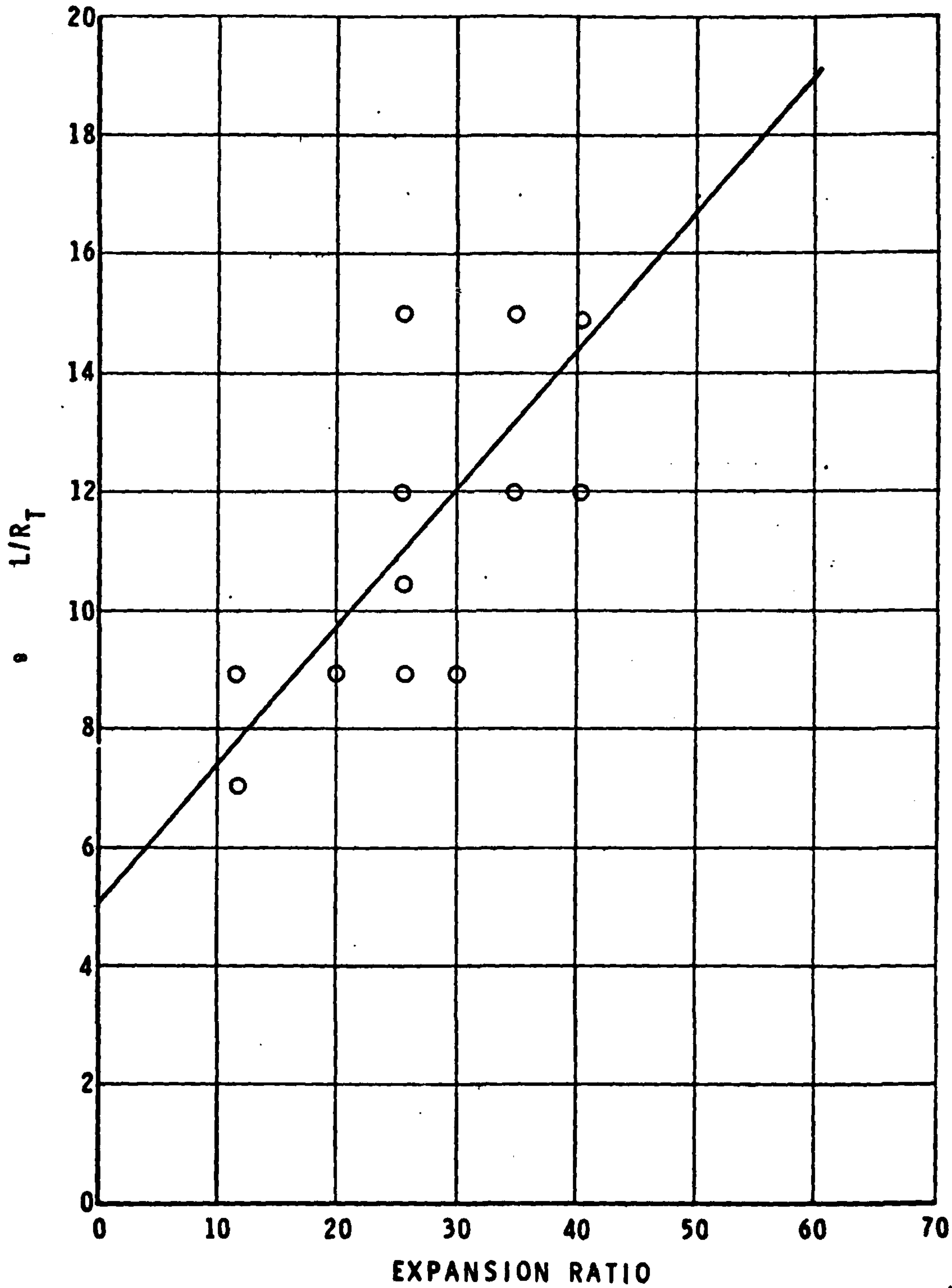
EXPERIMENTAL PROGRAM

- THIRTY (30) SUBSCALE MOTORS
- EXPANSION RATIOS FROM 12 TO 40
- L/R_T RATIOS FROM 7 TO 15
- INITIAL ANGLES FROM 23^0 TO 35^0
- THROAT RADIUS OF CURVATURE (R_2/R_T) FROM 0.6 TO 3.0
- INLET ANGLE FROM 15^0 TO 60^0

STATE-OF-THE-ART MOTORS



TEST MATRIX

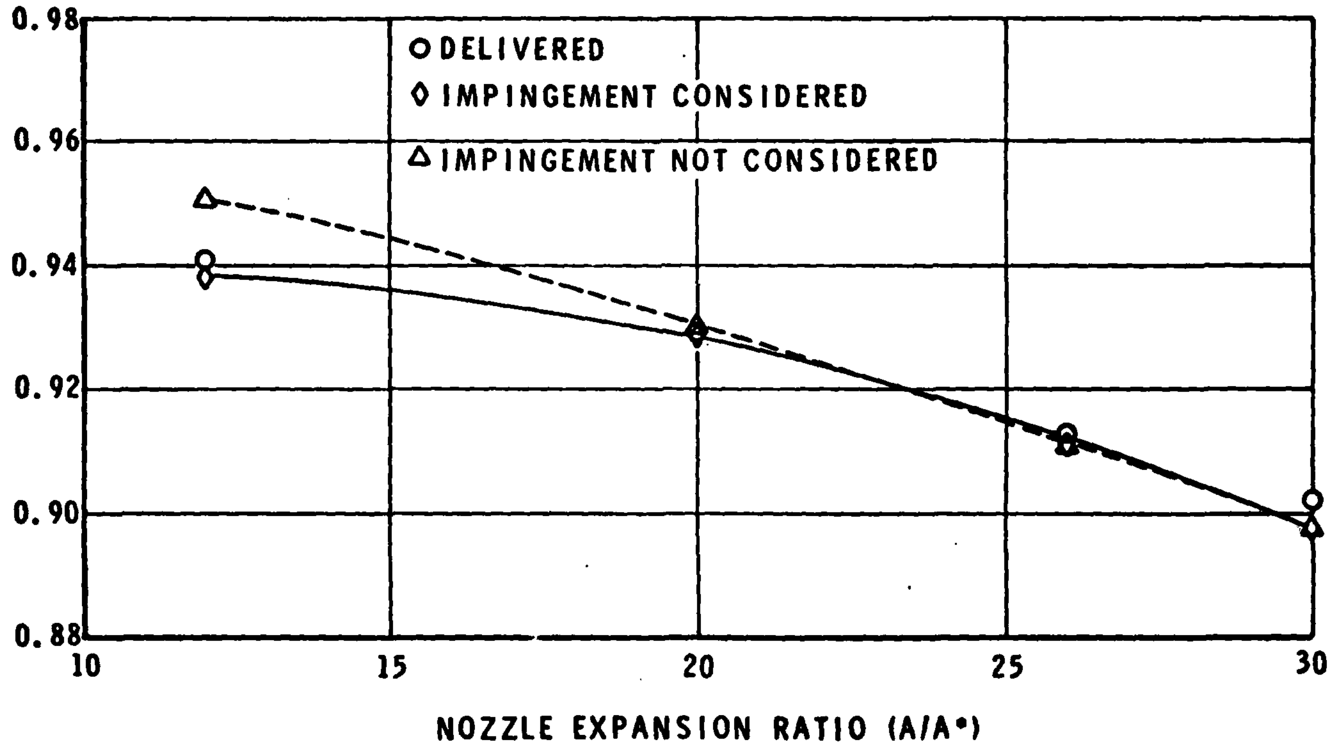


METHOD OF ANALYSIS

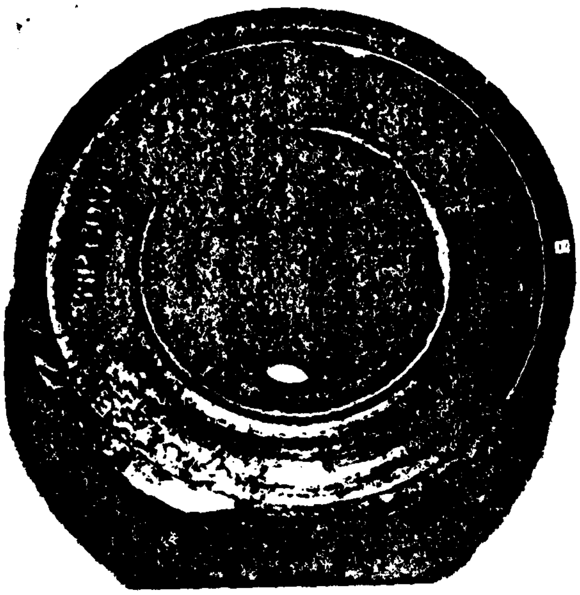
- CALCULATE AXIAL THRUST OF PARTICLES THAT IMPACT THE NOZZLE WALL
- $\Delta I_{SP} = \dfrac{F_{X\,(IMP)}}{\dot{m}}$
- $K = \dfrac{\dot{m}}{F_{X(IMP)}} \left(I_{SP(CALC)} - I_{SP(EXP)}\right)$

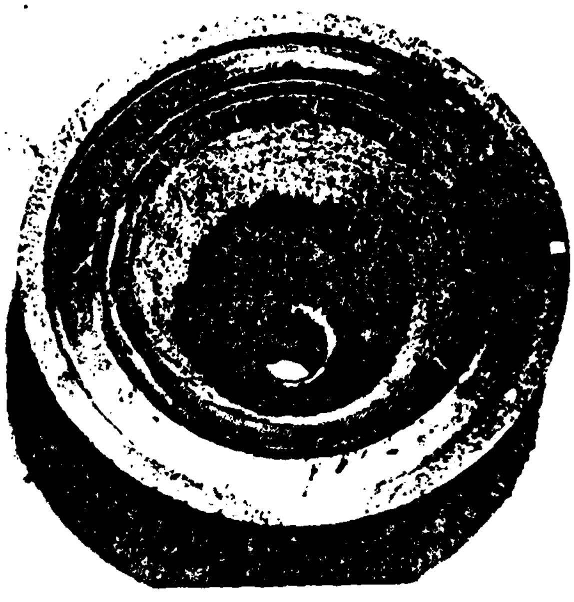
HERCULES Thiokol

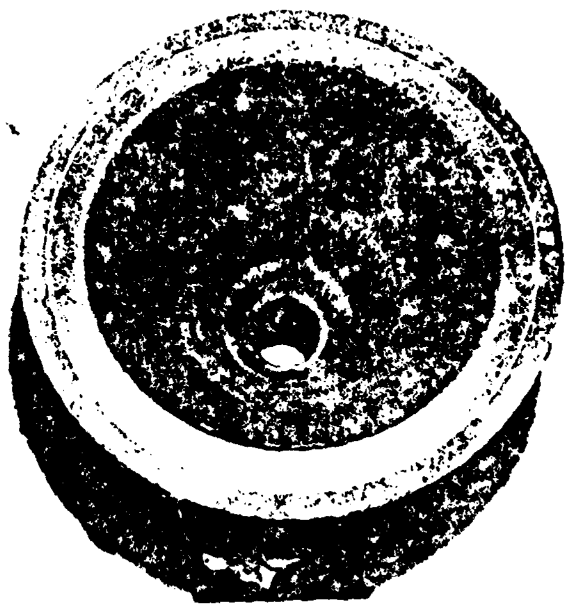
MOTOR EFFICIENCY VS A/A* FOR $L/R_T = 9$



EFFECT OF EXPANSION RATIO VARIATION

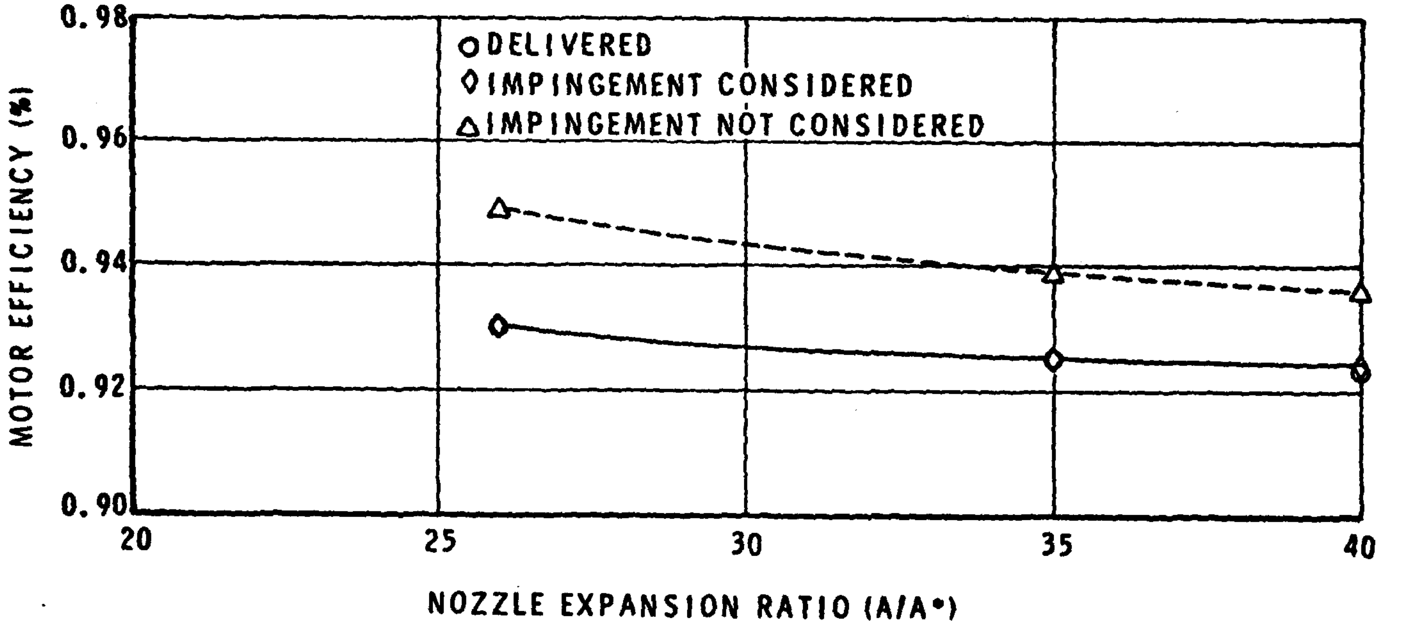






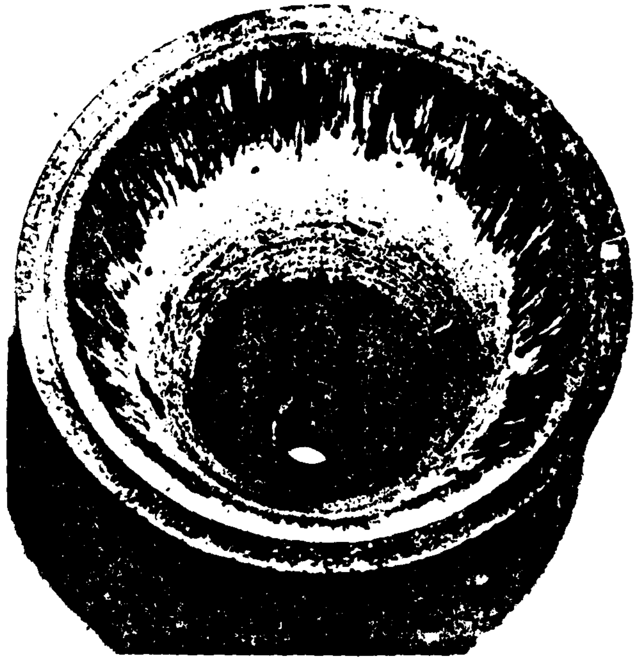
C4 HERCULES Thiokol

MOTOR EFFICIENCY VS A/A* FOR $L/R_T = 15$

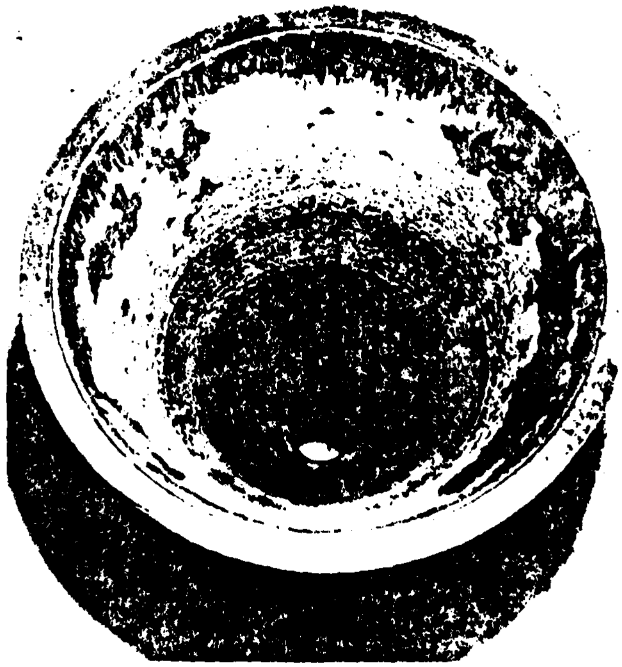


EFFECT OF EXPANSION RATIO VARIATION

A/A* 26

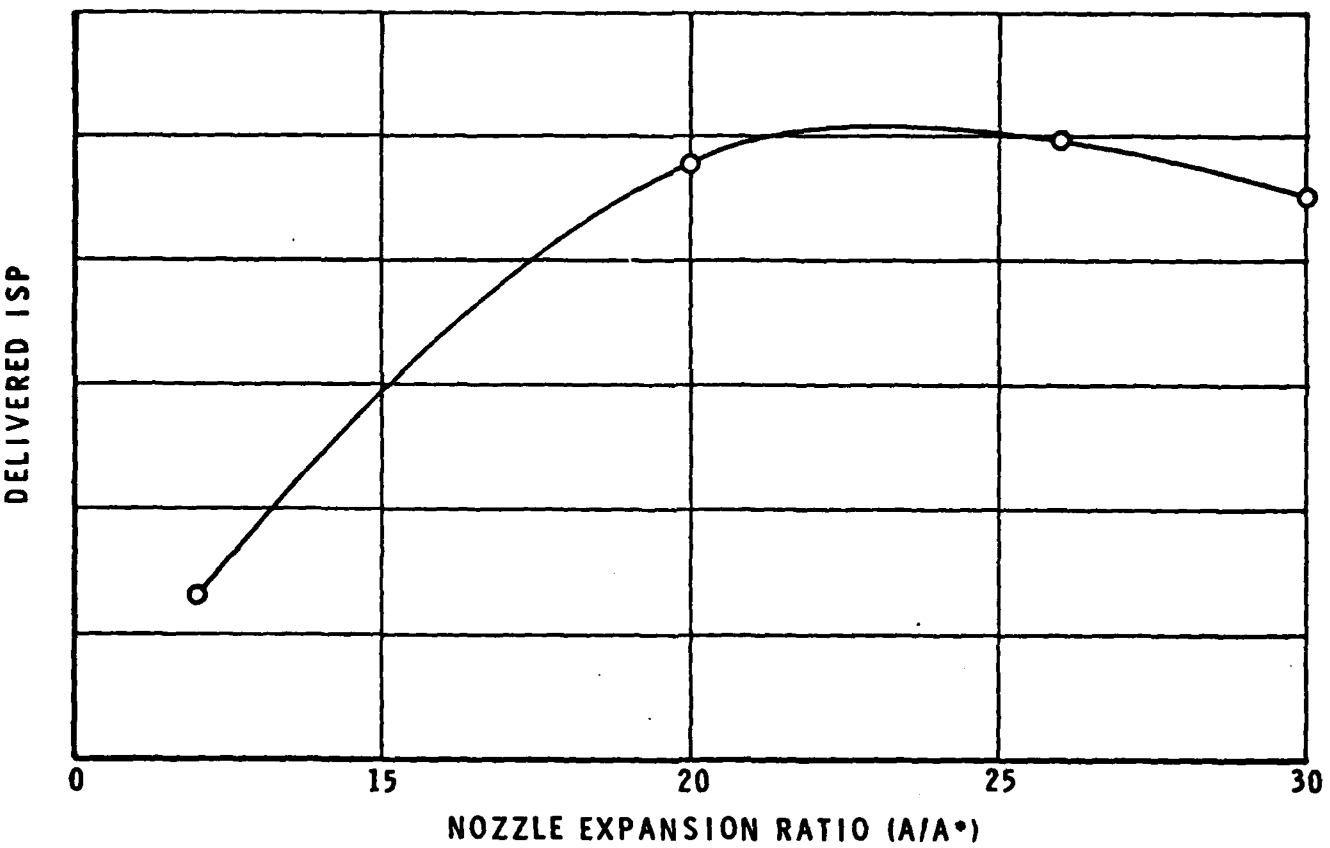


A/A* [illegible]

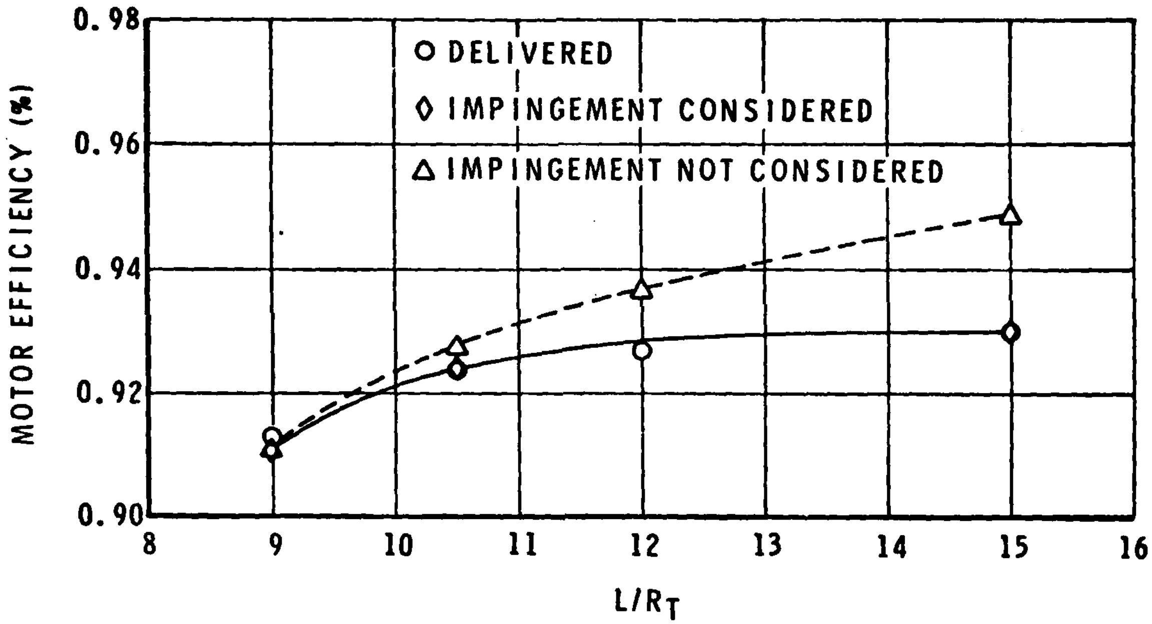


HERCULES Thiokol

I_{sp} VS NOZZLE EXPANSION RATIO $L/R_T = 9$

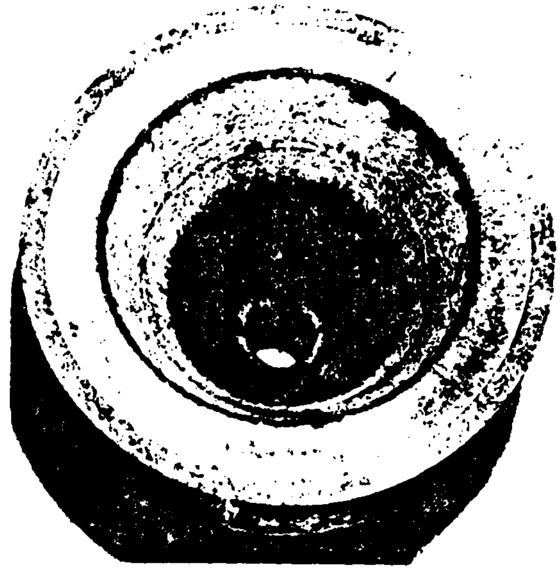


MOTOR EFFICIENCY VS NOZZLE L/R_T FOR E = 26

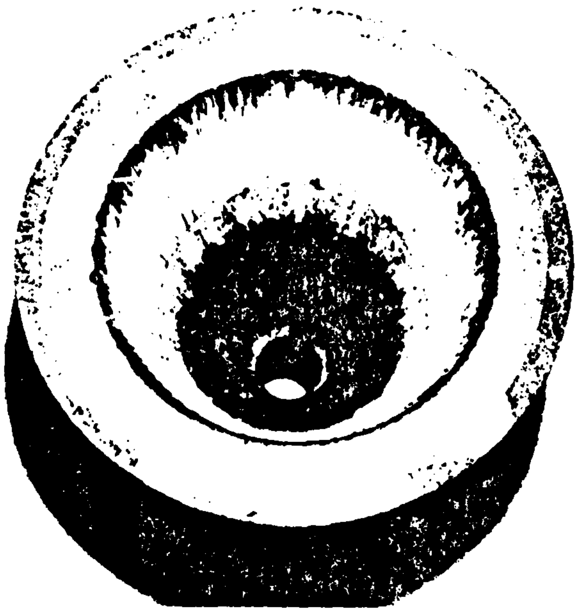


EFFECT OF NOZZLE LENGTH

[illegible]

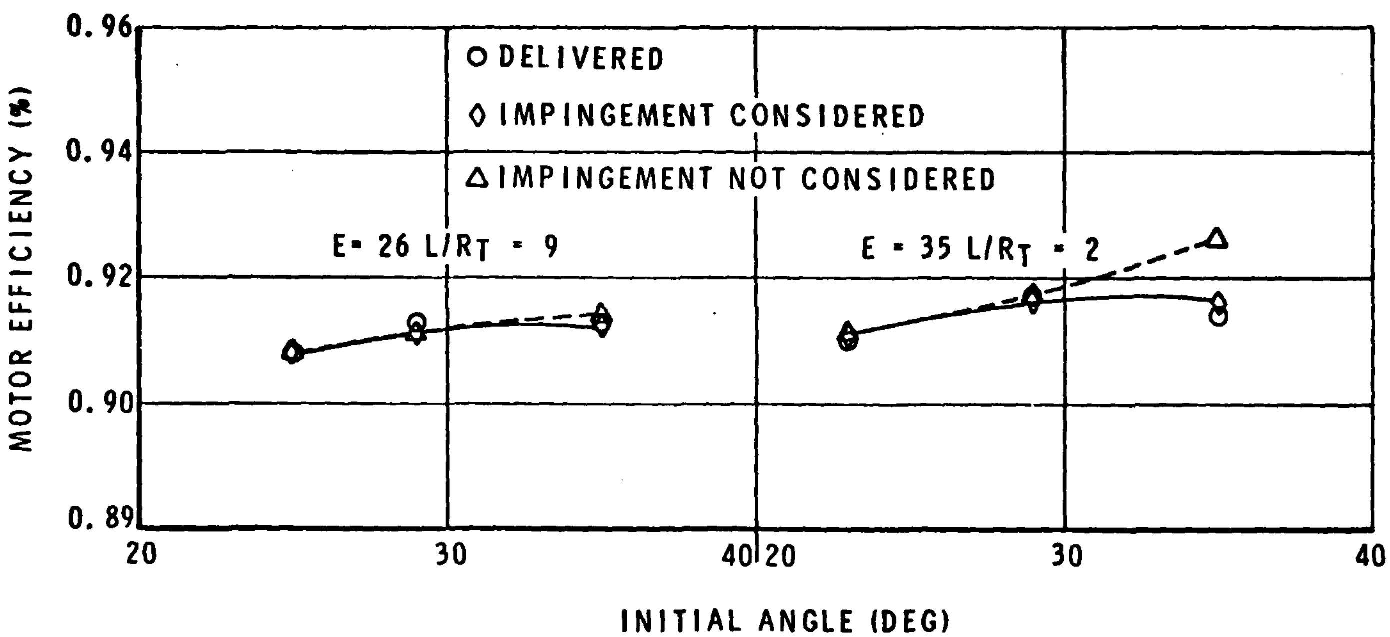


[illegible]



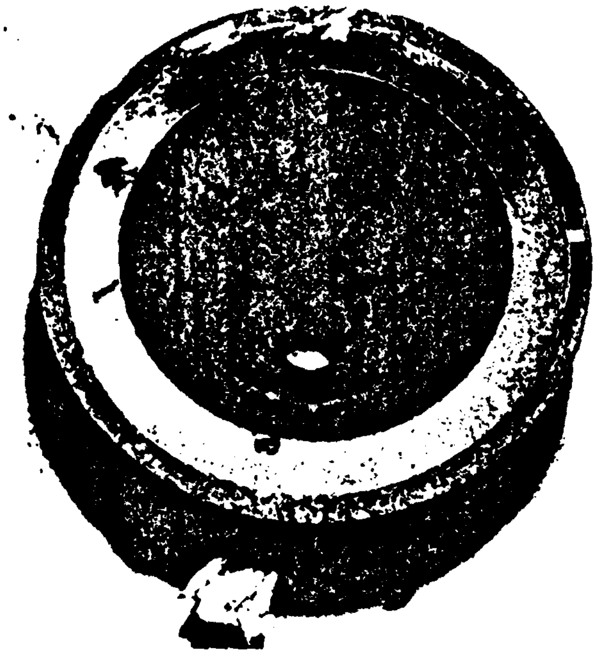
[illegible]

MOTOR EFFICIENCY VS INITIAL ANGLE

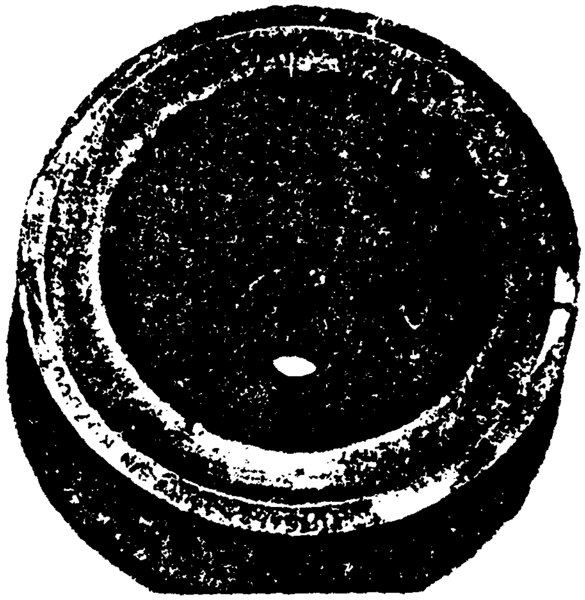


HERCULES Thiokol

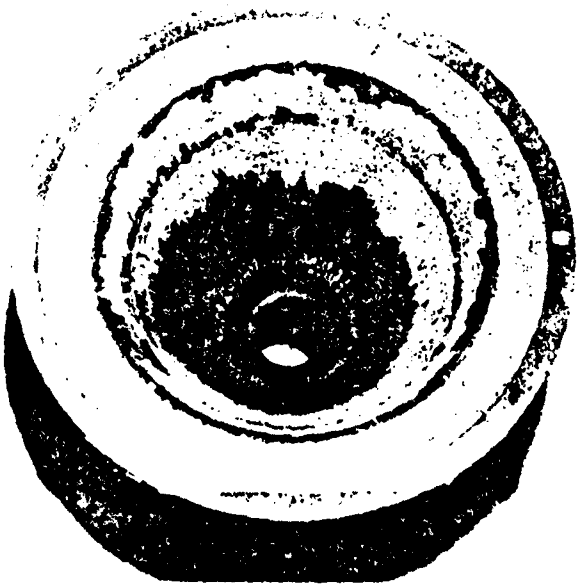
EFFECT OF INITIAL ANGLE VARIATION



θ_i 25 DEG



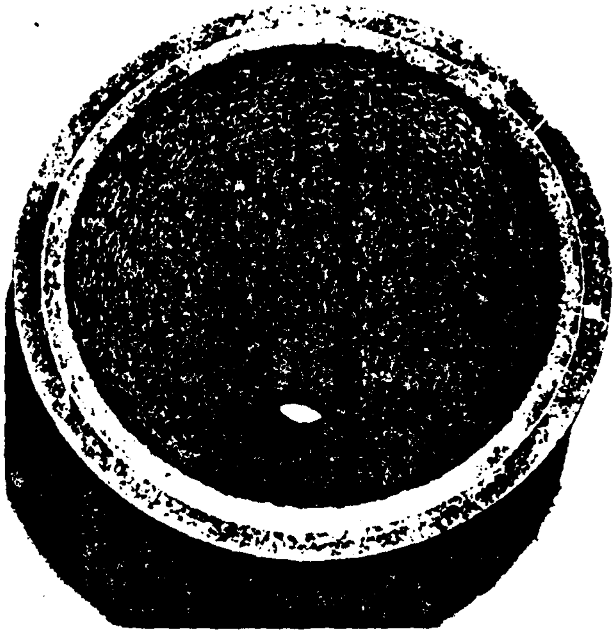
θ [illegible]



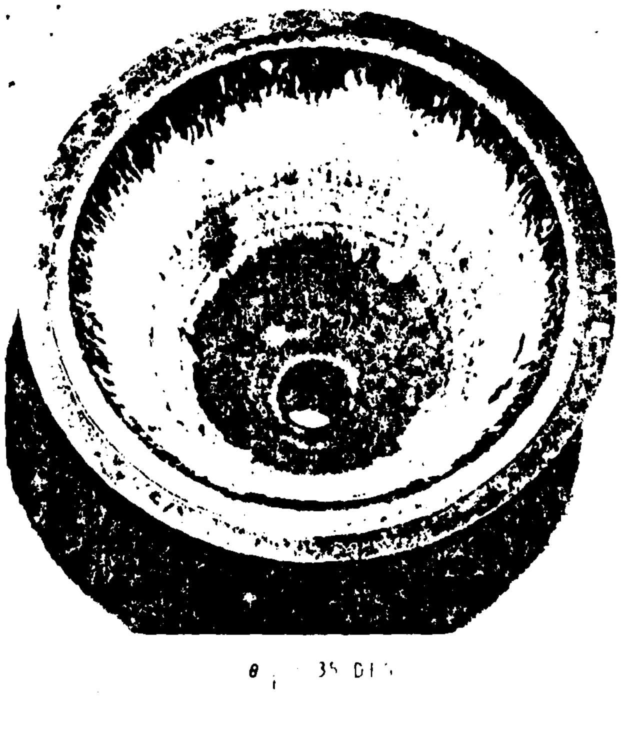
θ 35 DEG

EFFECT OF INITIAL ANGLE VARIATION

θ_i = 23 DEG



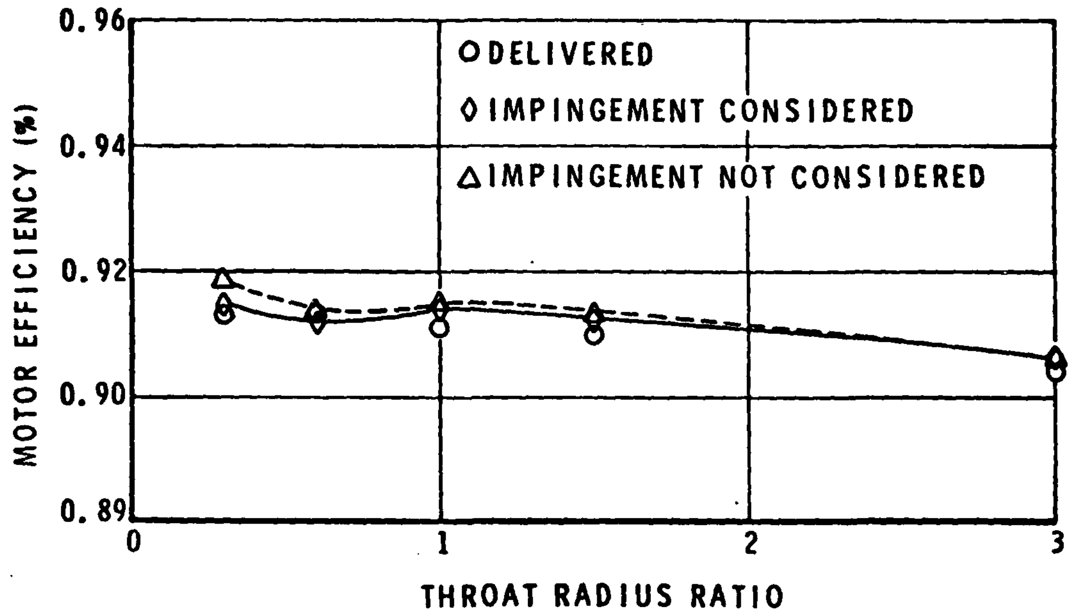
θ_i = 29 DEG



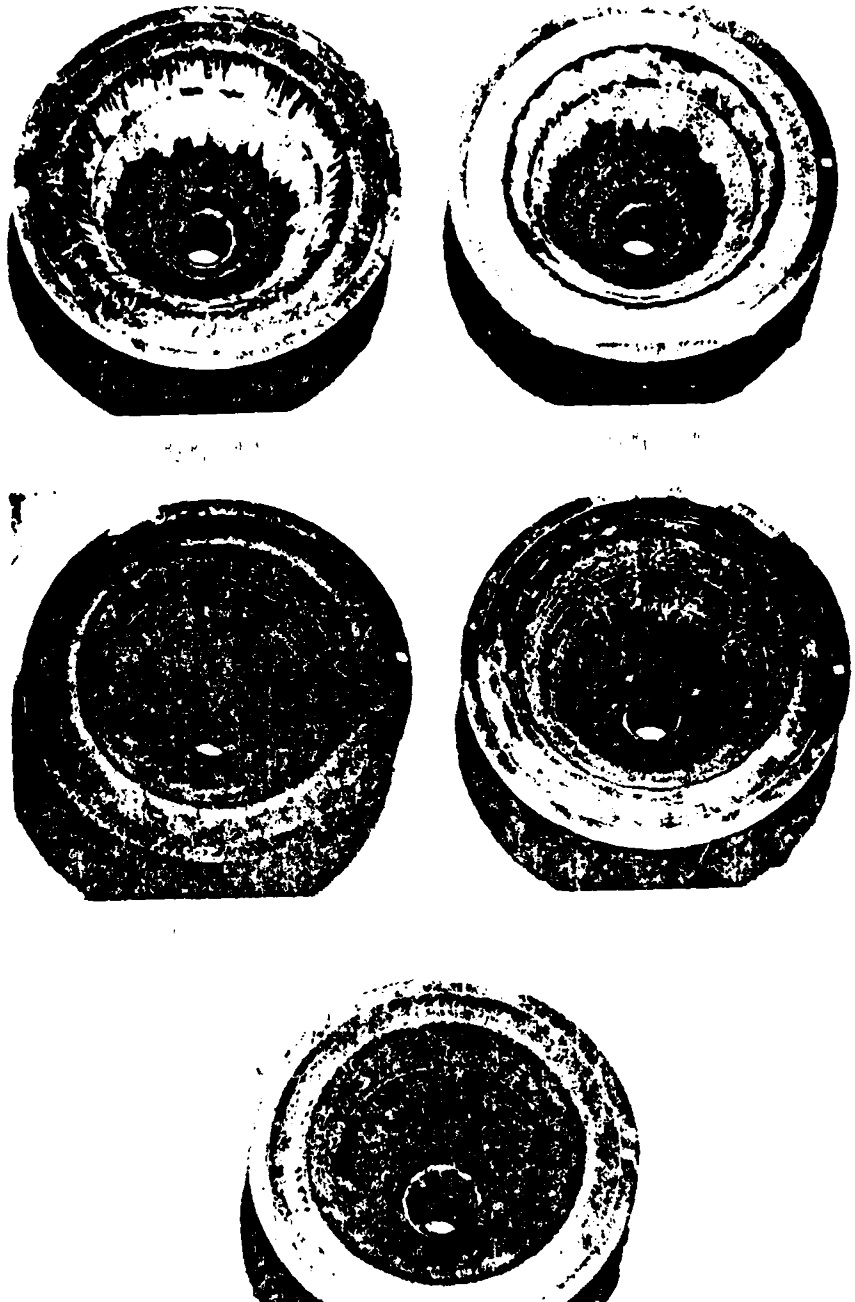
θ_i = 35 DEG

C4 HERCULES Thiokol

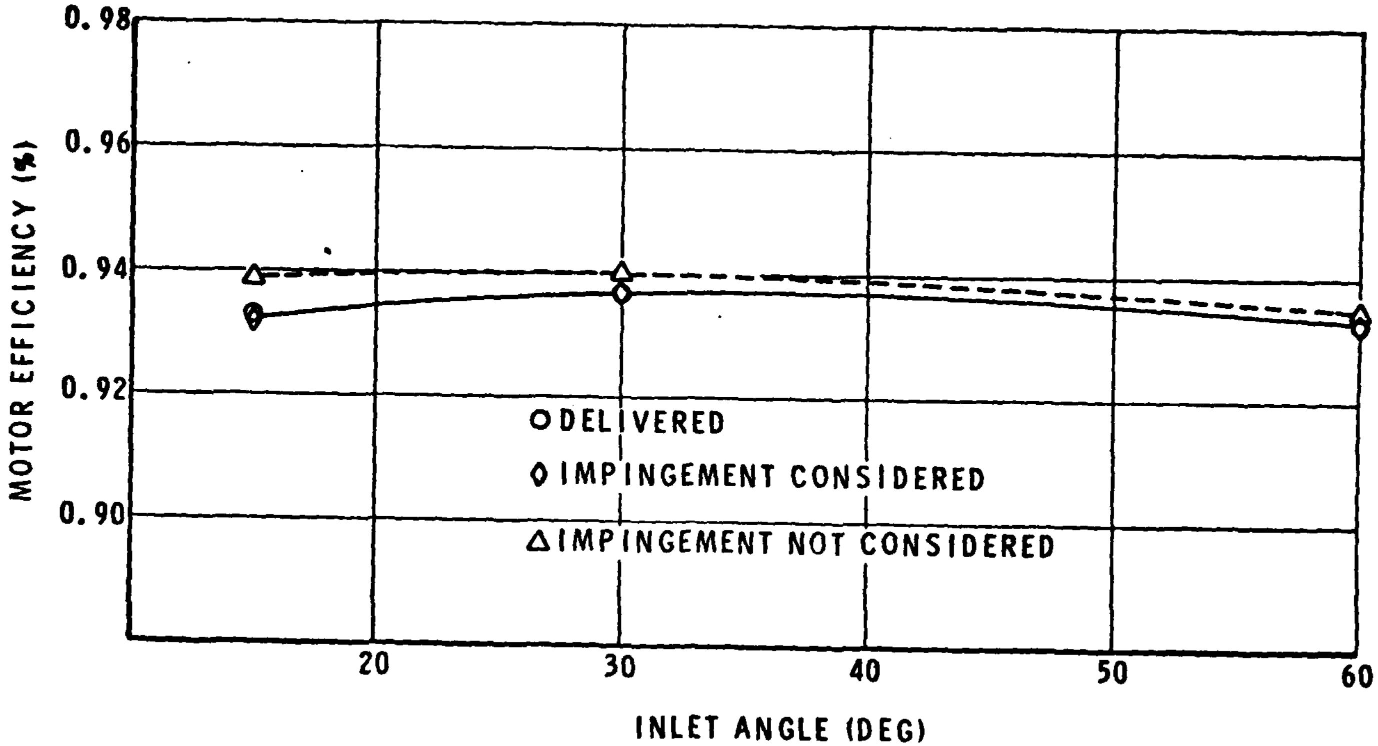
MOTOR EFFICIENCY VS R_2/R_T FOR $E = 26$; $L/R_T = 9$; $\theta i = 35$



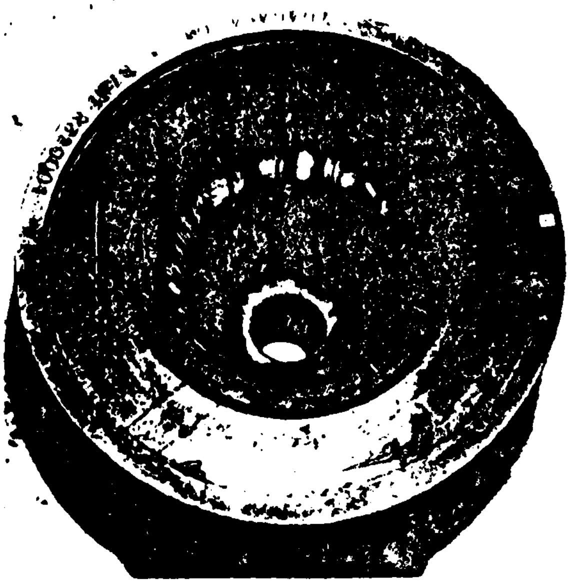
EFFECT OF NOZZLE DOWNSTREAM RADIUS RATIO



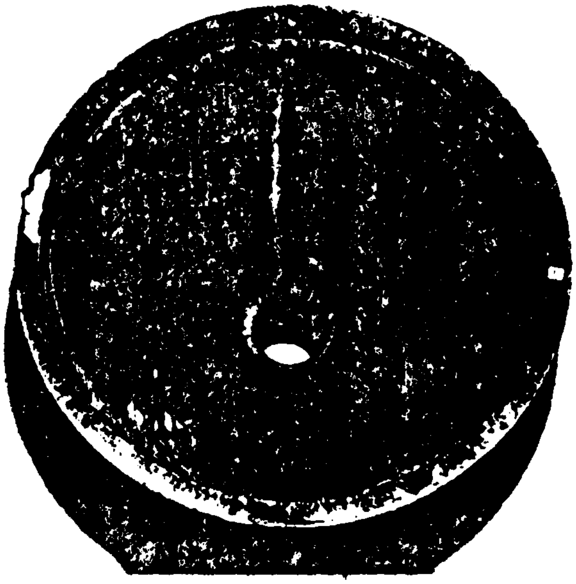
MOTOR EFFICIENCY VS INLET ANGLE FOR E = 12; L/R_T = 7



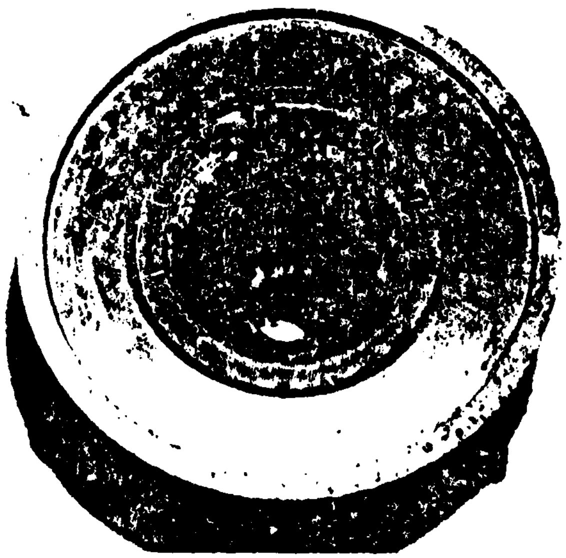
EFFECT OF INLET ANGLE VARIATION



θ_{INLET} 15 DEG



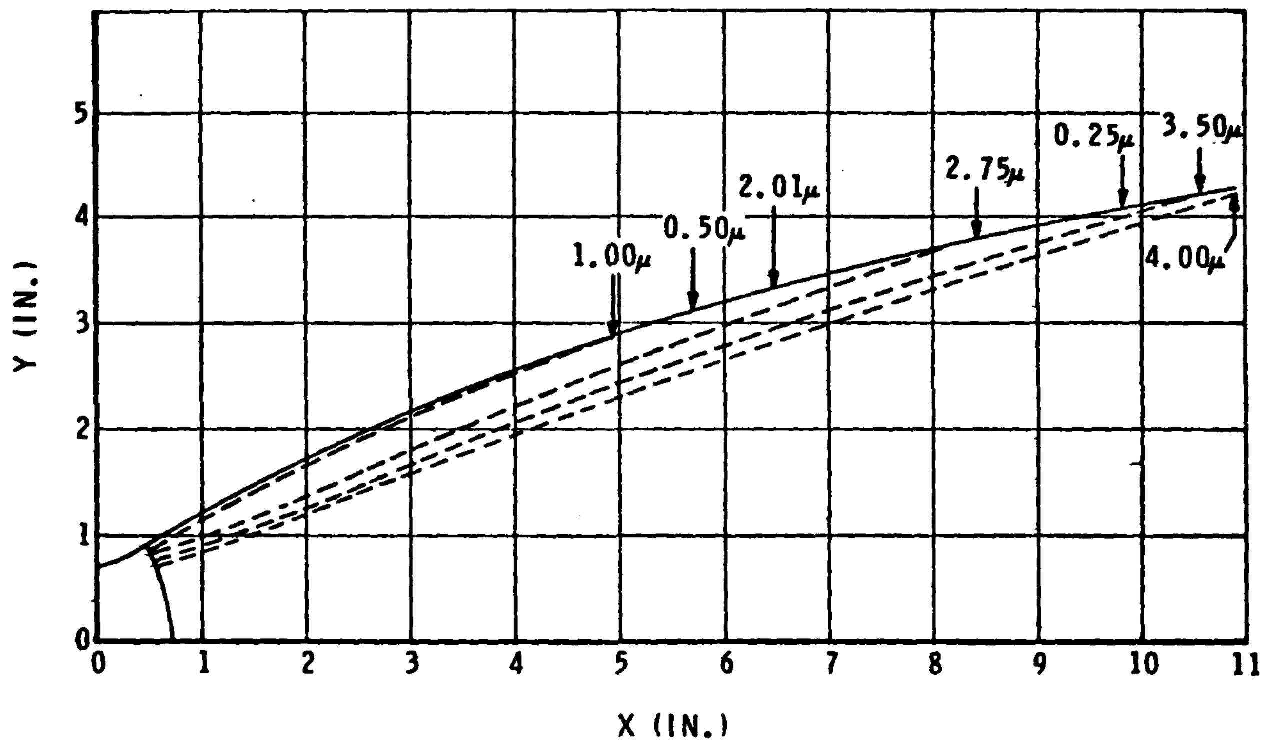
θ [illegible]



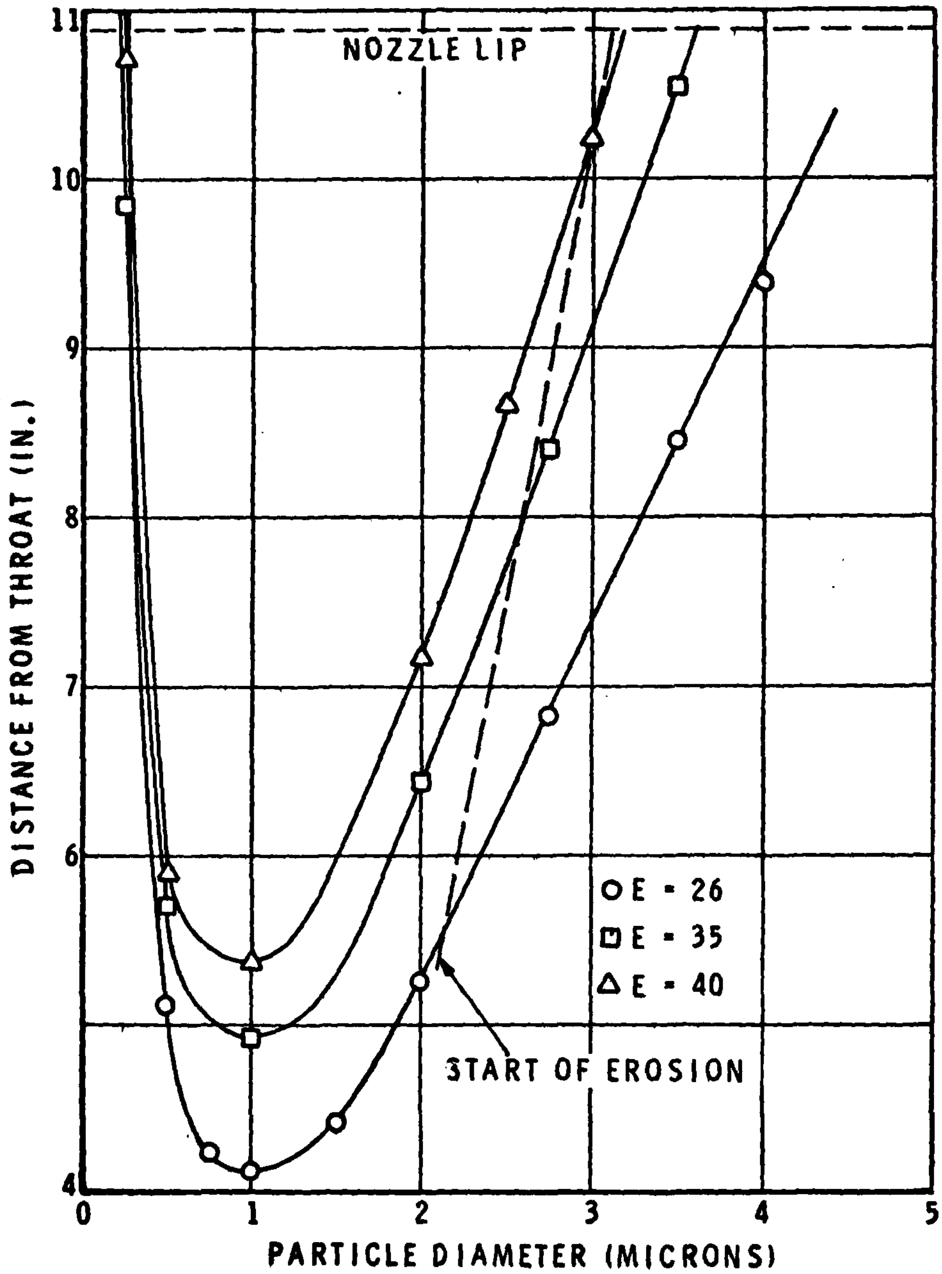
θ [illegible]

C 4
HERCULES Thiokol

PARTICLE LIMITING STREAMLINES



PARTICLE IMPACT POINTS



25

I_{sp} RESULTS

- ELEVEN MOTORS WITHOUT IMPINGEMENT WERE PREDICTED TO WITHIN 0.4%
- PREDICTIONS OF NINETEEN MOTORS WITH IMPINGEMENT WERE OFF AS MUCH AS 2%
- INCLUSION OF IMPINGEMENT LOSS REDUCED PREDICTION ERROR TO LESS THAN 0.4%

CONCLUSIONS

- IMPINGEMENT CAN CAUSE SIGNIFICANT THRUST LOSSES
- ALL OF THE IMPULSE OF IMPACTING PARTICLES IS NOT LOST
- THE EFFECT OF IMPINGEMENT ON I_{SP} CAN BE CALCULATED
- IMPINGEMENT IS AN IMPORTANT FACTOR IN DESIGNING AN OPTIMUM CONTOUR

NOZZLELESS PERFORMANCE MECHANISMS

PRESENTED BY

I. M. PROCINSKY

ATLANTIC RESEARCH CORPORATION

FEBRUARY 14, 1980

NOZZLELESS MOTOR PERFORMANCE MECHANISMS

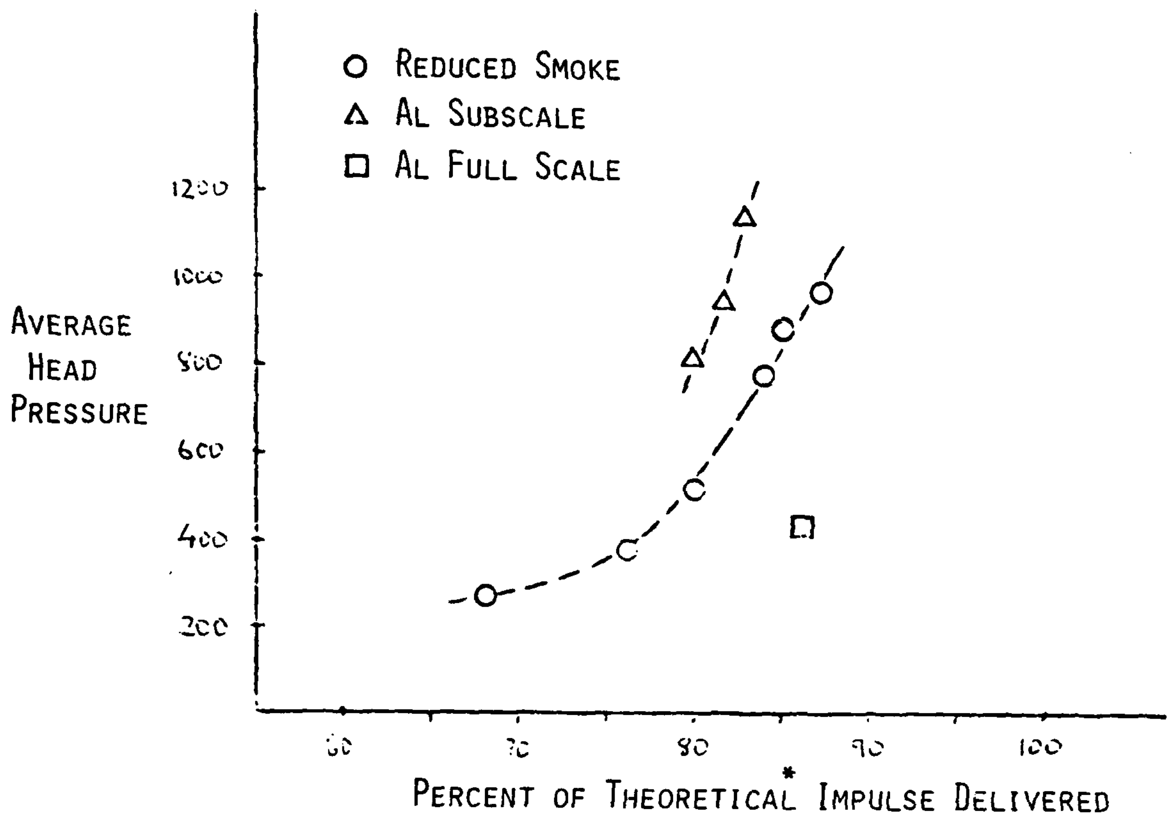
CRITICAL PHENOMENA

- EROSIVE BURNING
- GRAIN DEFLECTION
- COMBUSTION EFFICIENCY - REDUCED SMOKE
  - METAL LOADED

COMBUSTION AND OPERATING EFFICIENCIES

- Nozzleless Motors Operate Between 65 and 85% of Theoretical I_{SP}
  - Variable Expansion Ratio (Avg. less than 4)
  - Regressive Pressure (Avg. Pressure Less Than .5 of Max)
  - Dramatic Improvement in Performance Can Be Obtained By Using Propellant with Lower Pressure Exponent
- In Metallized Propellants the Effect of Initial Particle Size, Agglomeration, and Residence Time Has Been Shown To Be Significant.
  - Subscale/Full Scale Effects Obvious In Aluminum Propellants
  - Apparent Burn Rate Shifts and Performance Improvements With Zirconium Propellants

NOZZLELESS DELIVERED IMPULSE VS AVERAGE HEAD PRESSURE



*CALCULATED AS IDEALLY EXPANDED 1000 - 14.7 PSI

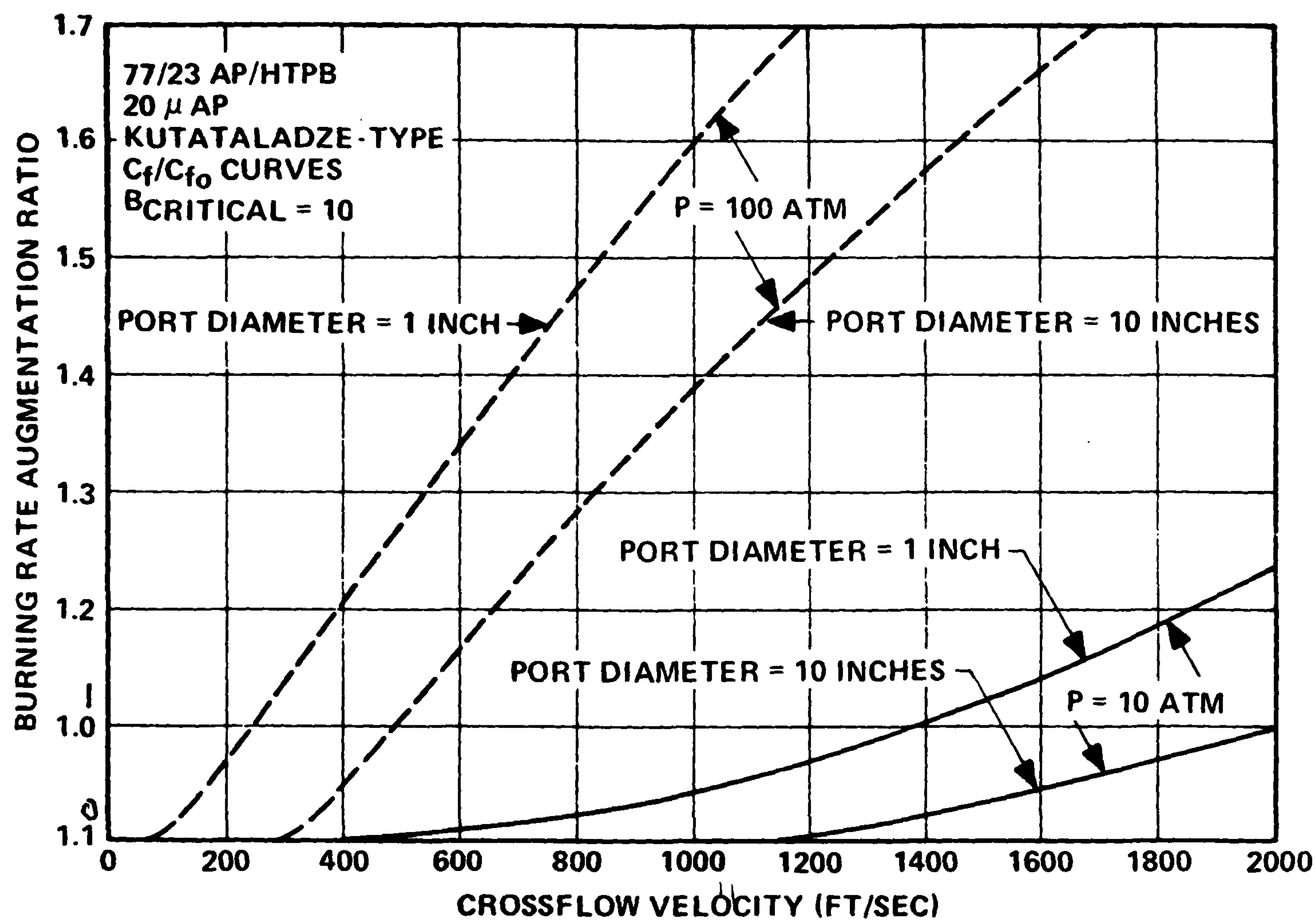
GRAIN DEFLECTION

- Secondary Effect at Pressures Below 500 psig
- Current Model Uses Static Deflection Calculations Adjusted Linearly for Local Pressure and Web Remaining
- Limited Data Shows Actual Deflections Only Fraction (< 1/3) of Calculated Value
- Motor Data Does Show Ballistics Shape Variation With Propellant Physical Properties
- New Model Development Will Include:
  - Iterative Analysis of Pressure/Contours Interaction
  - Visco Elastic and Dynamic Effects
    - TEXGAP
    - Hondo (Sandia, Two Dimensional Finite Deformation and Dynamic)
    - Poissons Ratio Correlations
    - Coupling Between Deflection and Pressure
    - Actual Propellant Relaxation Modulus. Modeling Using Prony Series Fit.

EROSIVE BURNING

- Significant Factor in Motors With:
  - Burn Rate < 1.0 in/sec at 1000 psig
  - Pressure > 1000 psig
  - Augmentation Proportional to Pressure
- Model Currently Used Empirically Dependent - 3 Constants
- Model Goals:
  - Base Burn Rate from Constituents
  - Handle Uni-Modal and Multi-Modal Oxidizer, and Both Metal and Non-Metal Compositions
  - Requires Strand Data Only for Catalyzed Systems

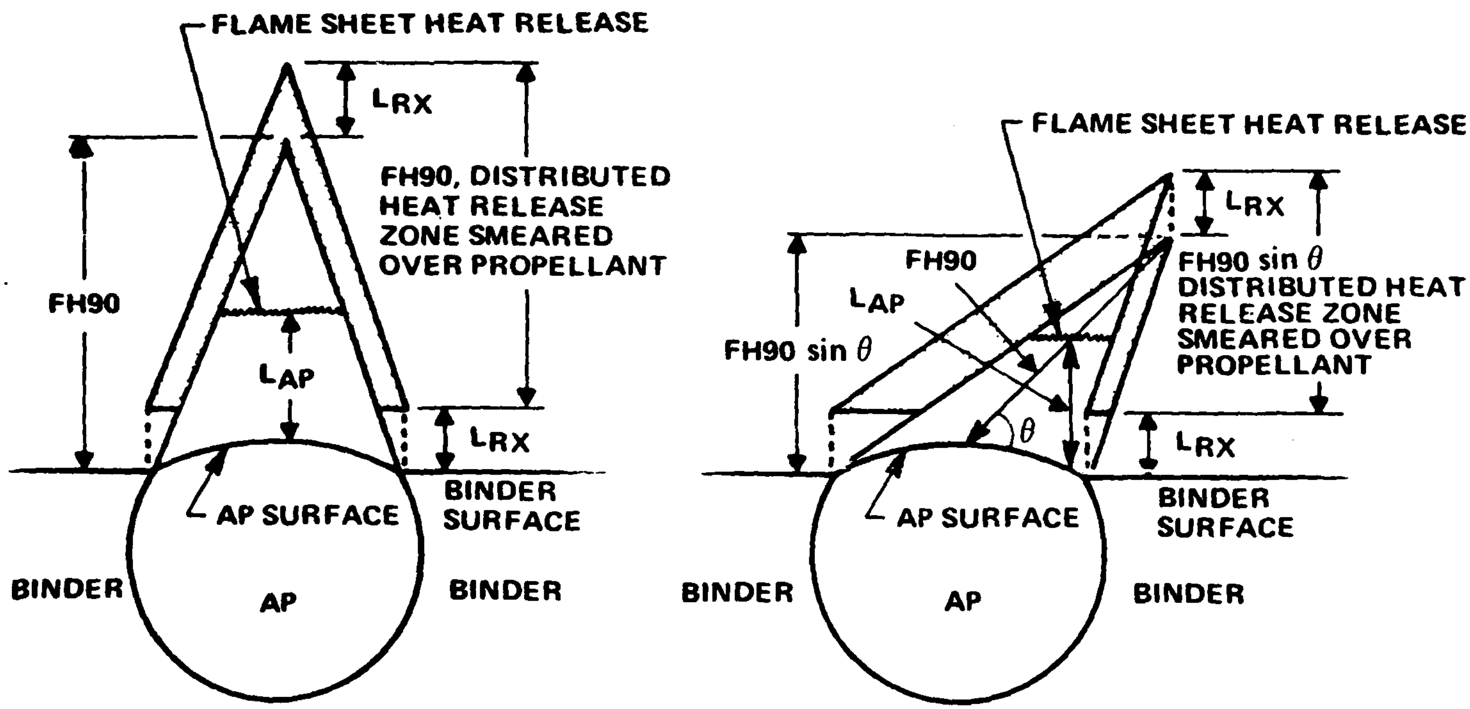
SCALING EFFECTS ON PREDICTED EROSIVE BURNING



PROPELLANT FORMULATION MATRIX TESTED

FORMULATION	COMPOSITION	RATIONALE
4525	73/27 AP/HTPB, 20 MICRON AP	BASELINE FOMULATION, FLAME TEMPERATURE = 1667°K
5051	73/27 AP/HTPB, 200 MICRON AP	COMPARE WITH 4525 FOR AP SIZE EFFECT AND BASE BURNING RATE EFFECT
4685	73/27 AP/HTPB, 5 MICRON AP	COMPARE WITH 4525 AND 5051 FOR AP SIZE EFFECT AND BASE BURNING RATE EFFECT
4869	72/26/2 AP/HTPB/Fe_2O_3, 20 MICRON AP	COMPARE WITH 4525 FOR BASE BURNING RATE EFFECT AT CONSTANT AP SIZE
5542	77/23 AP/HTPB, 20 MICRON AP	COMPARE WITH 4525 FOR MIXTURE RATIO AND FLAME TEMPERATURE EFFECT AT CONSTANT AP SIZE. T=2065°K
5565	82/18 AP/HTPB, 13.65% 90 MICRON AP, 68.35% 200 MICRON AP	AP SIZES CHOSEN TO MATCH BASE BURNING RATE OF 4525. COMPARE WITH 4525 FOR MIXTURE RATIO AND FLAME TEMPERATURE EFFECT. T=2575°K
5555	82/18 AP/HTPB, 41% 1 MICRON AP, 41% 7 MICRON AP	COMPARE WITH 5565 FOR EFFECT OF BASE BURNING RATE.
6626	74/21/5 AP/HTPB/AL, 70% 90 MICRON AP, 4% 200 MICRON AP	SOME FLAME TEMPERATURE AND BASE BURNING RATE AS 5565. COMPARE WITH 5565 FOR AL EFFECT.

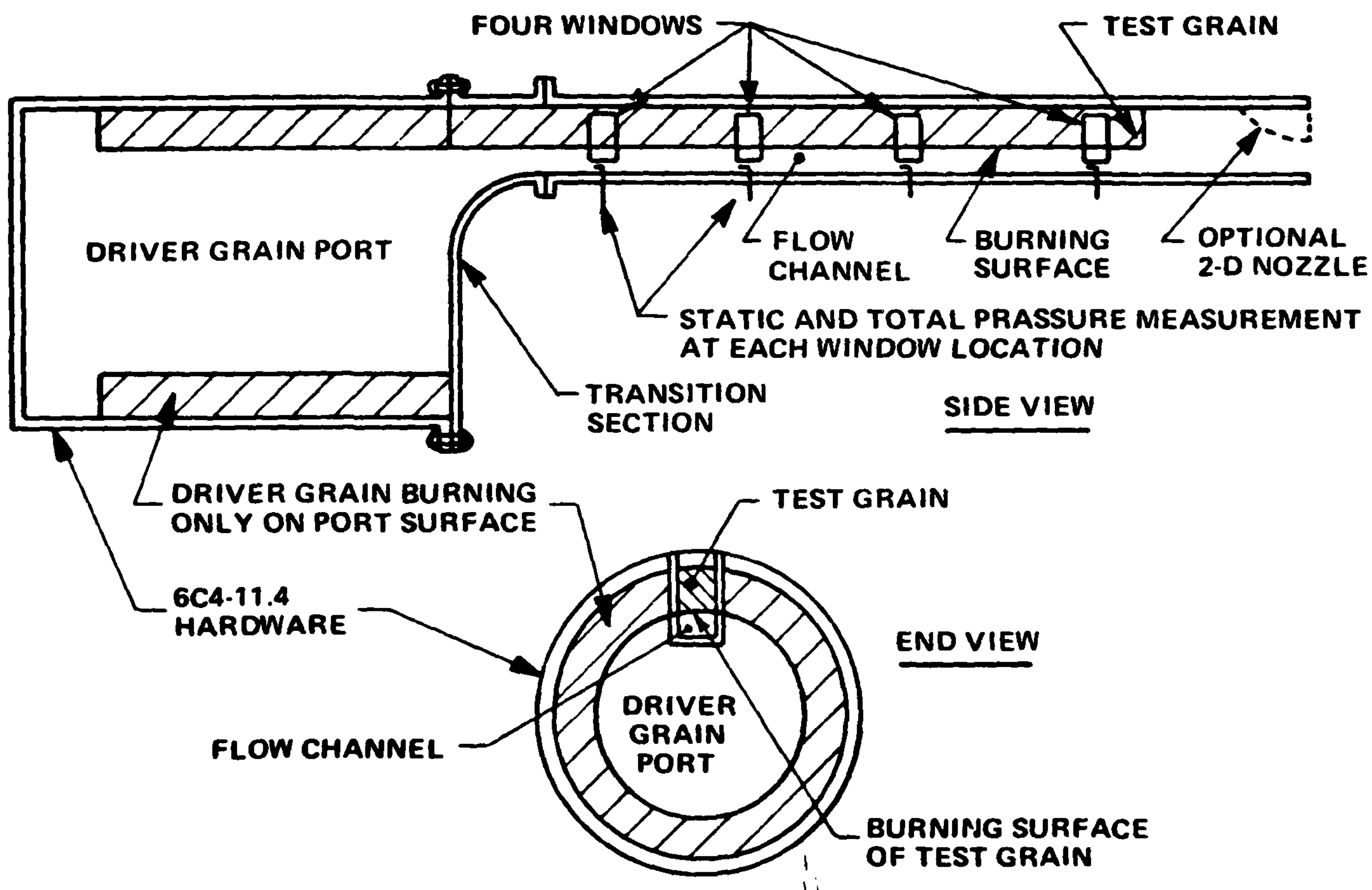
SCHEMATIC OF BURNING COMPOSITE PROPELLANT POSTULATED FLAME STRUCTURE, WITH AND WITHOUT CROSSFLOW



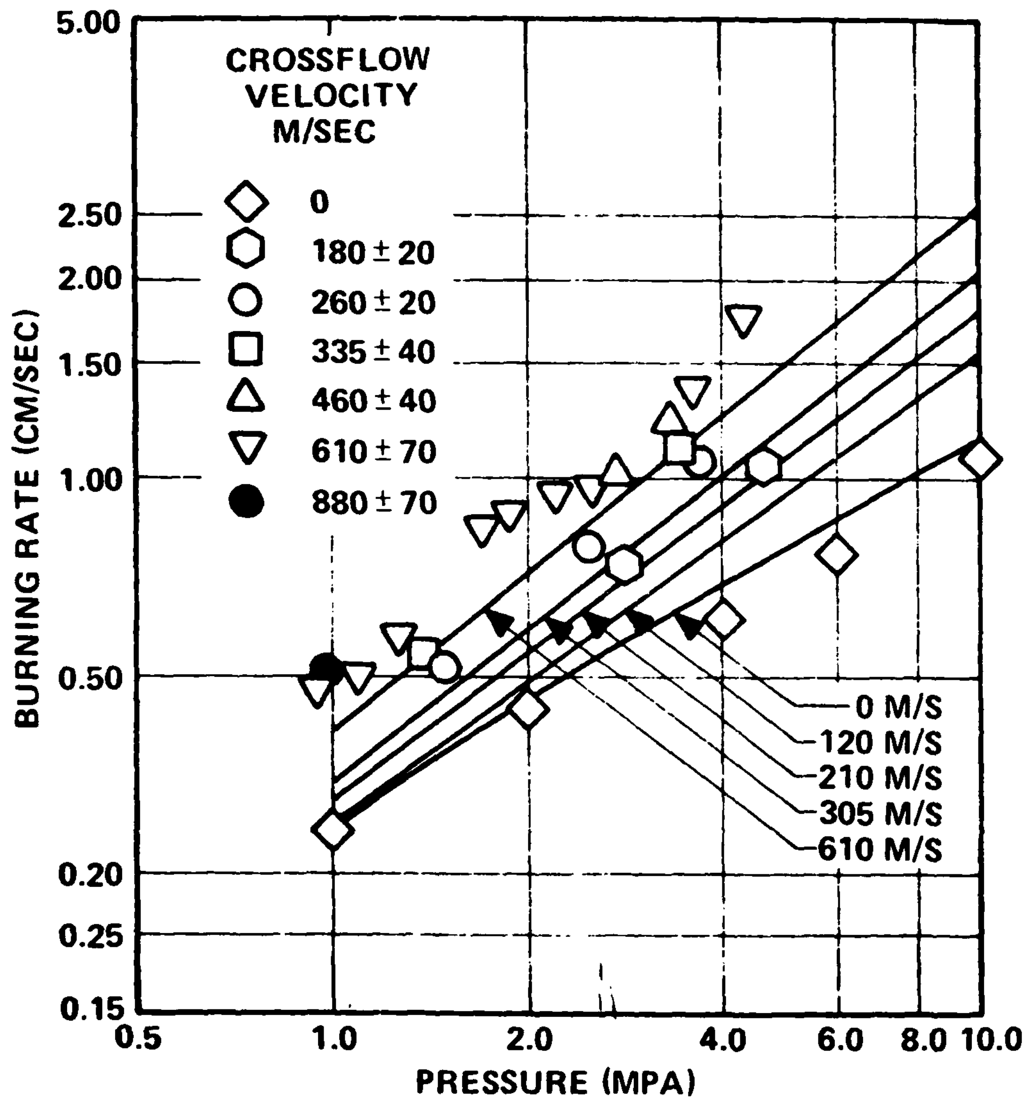
(a) NO CROSS FLOW CASE

(b) CROSS FLOW CASE

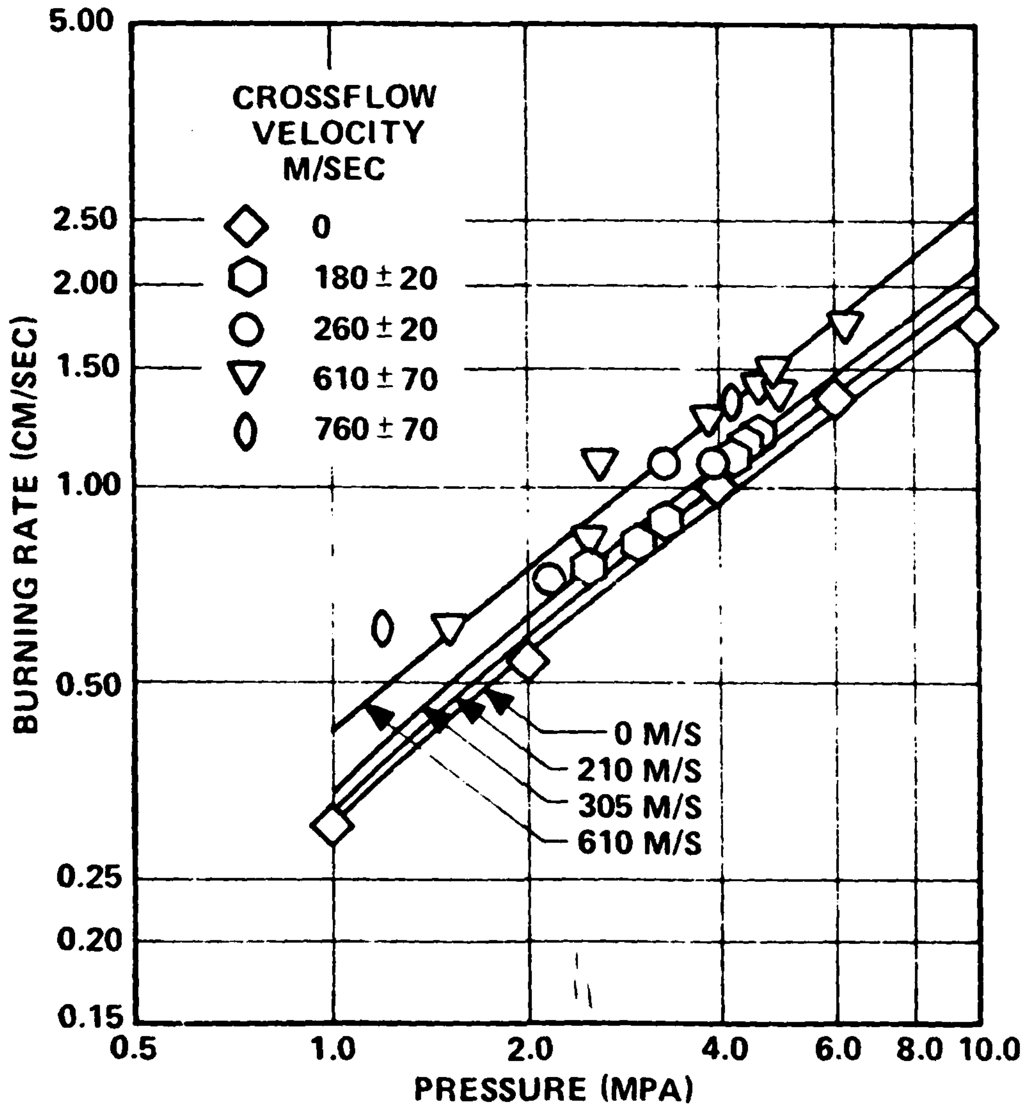
SCHEMATIC DRAWING OF EROSIVE BURNING TEST APPARATUS



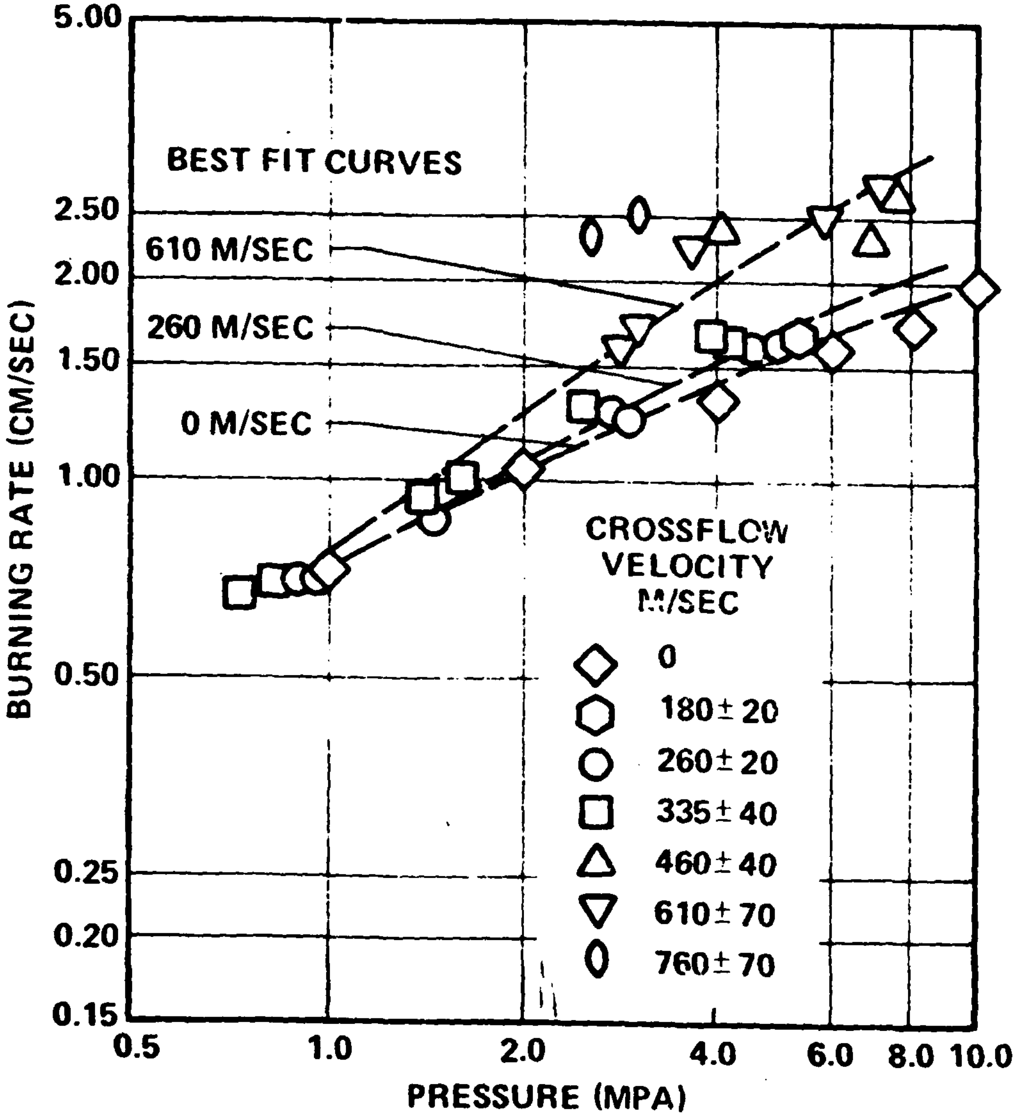
BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 4525 (73/27 AP/HTPB, 20 MICRON AP)



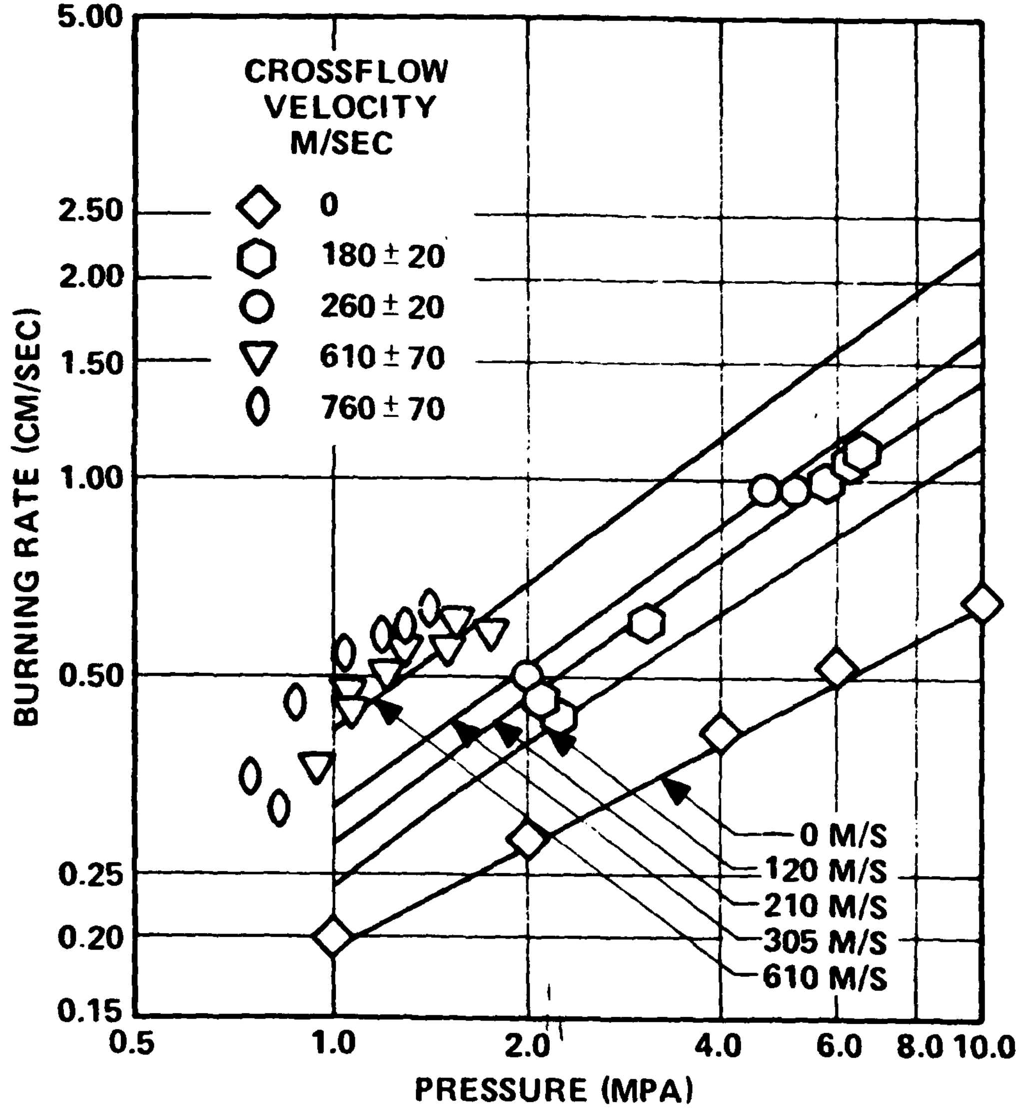
BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 4685 (73/27 AP/HTPB, 5 MICRON AP)



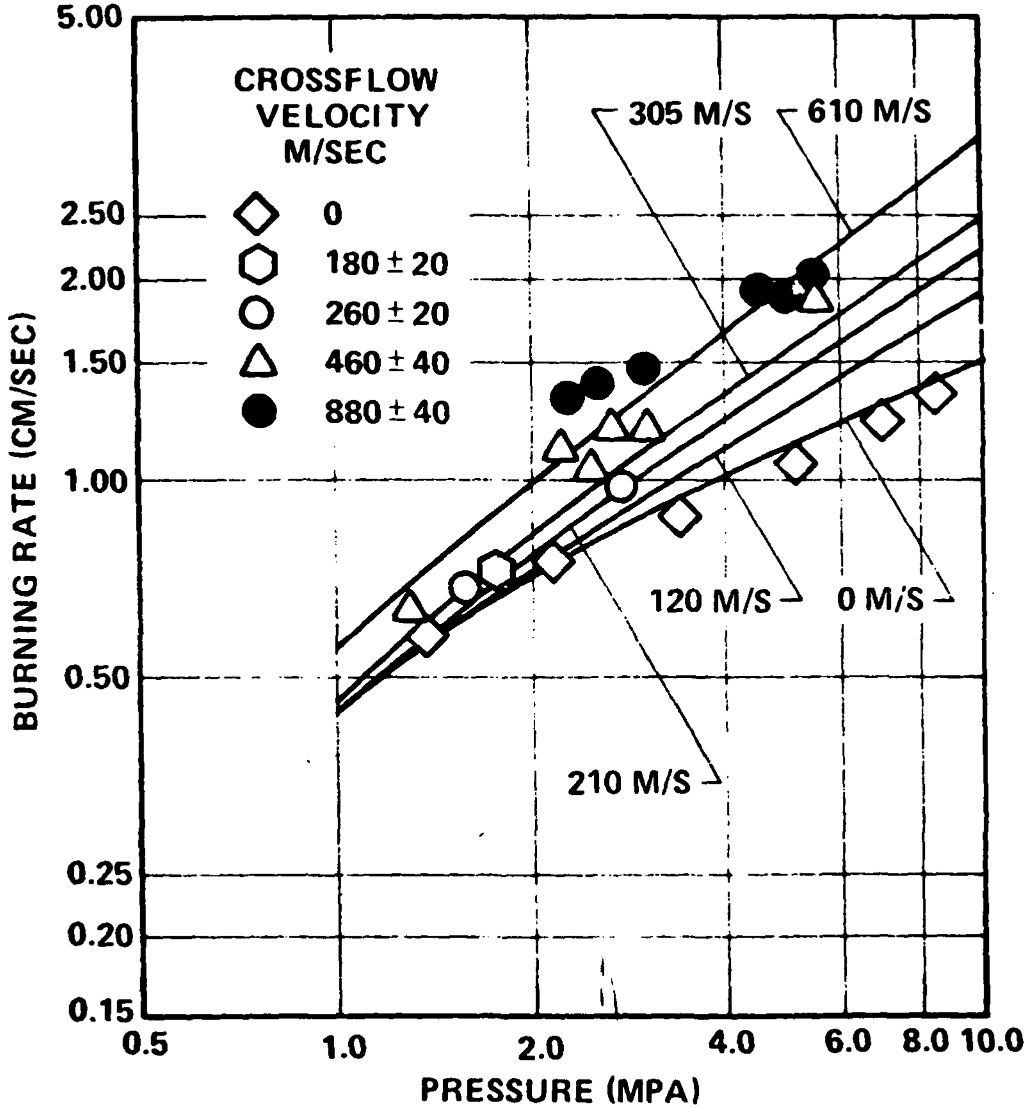
BURNING RATE (NO PREDICTIONS)
FOR FORMULATION 4869 (72/26/2 AP/HTPB/Fe_2O_3, 20 MICRON AP)



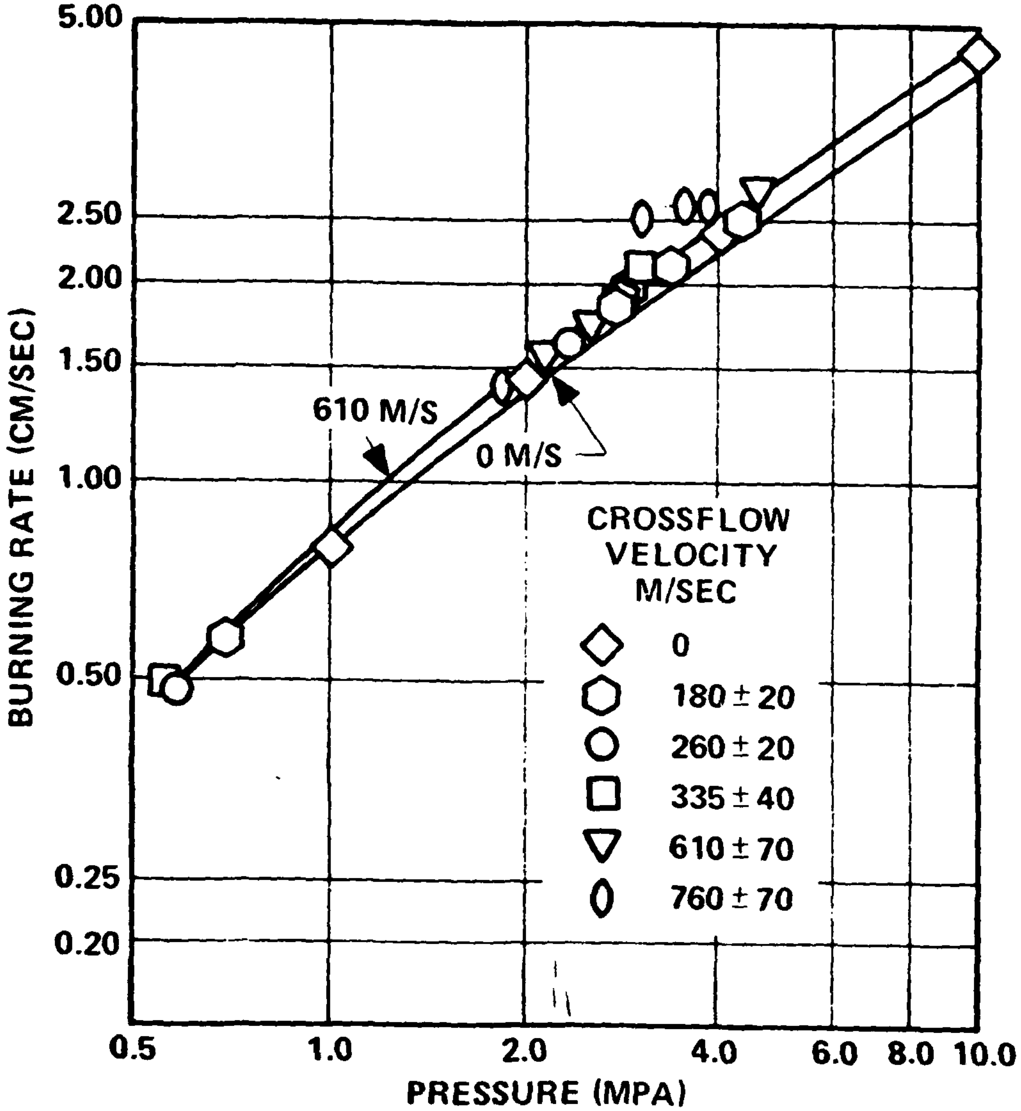
BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 5051 (73/27 AP/HTPB, 200 MICRON AP)



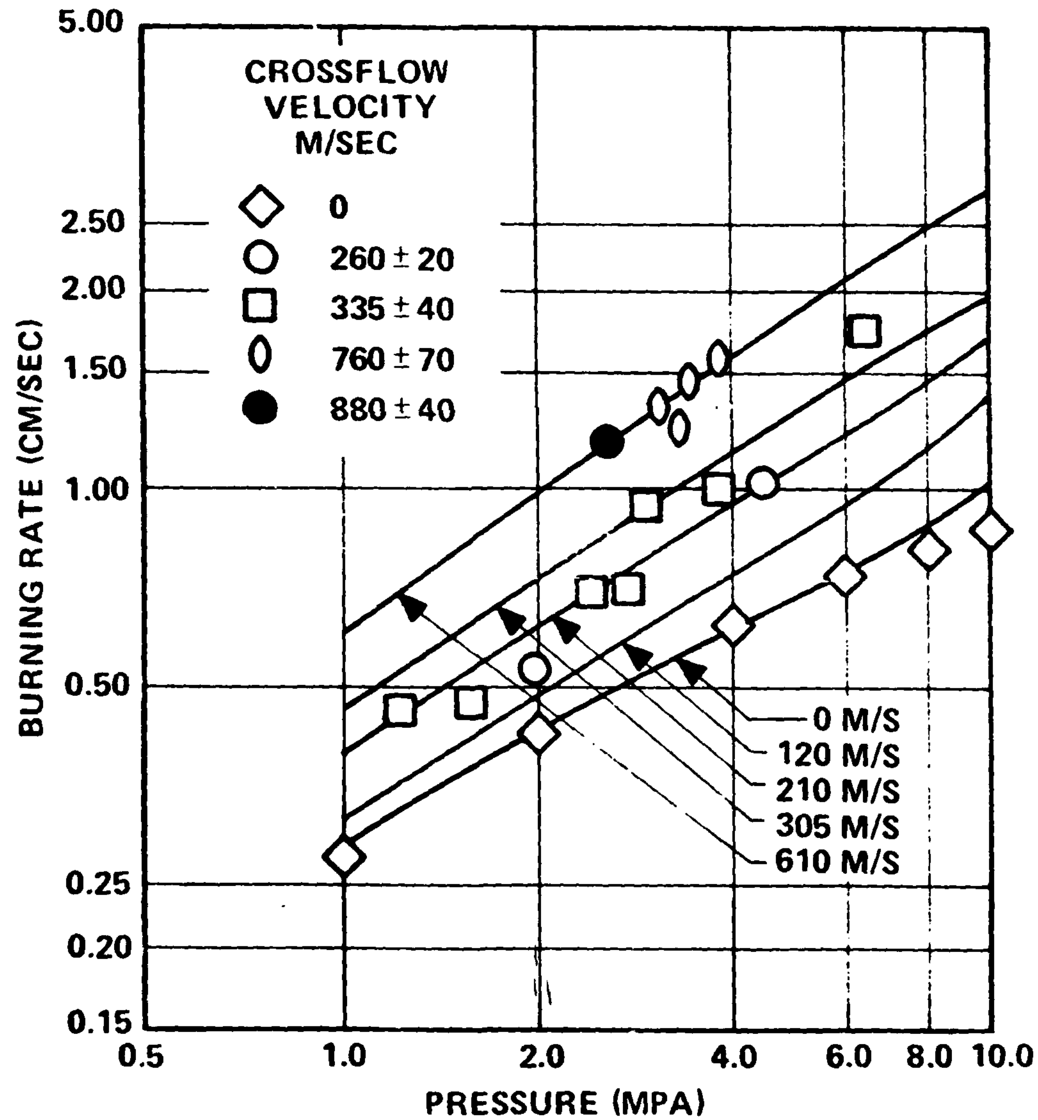
BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 5542 (77/23 AP/HTPB, 20 MICRON AP)



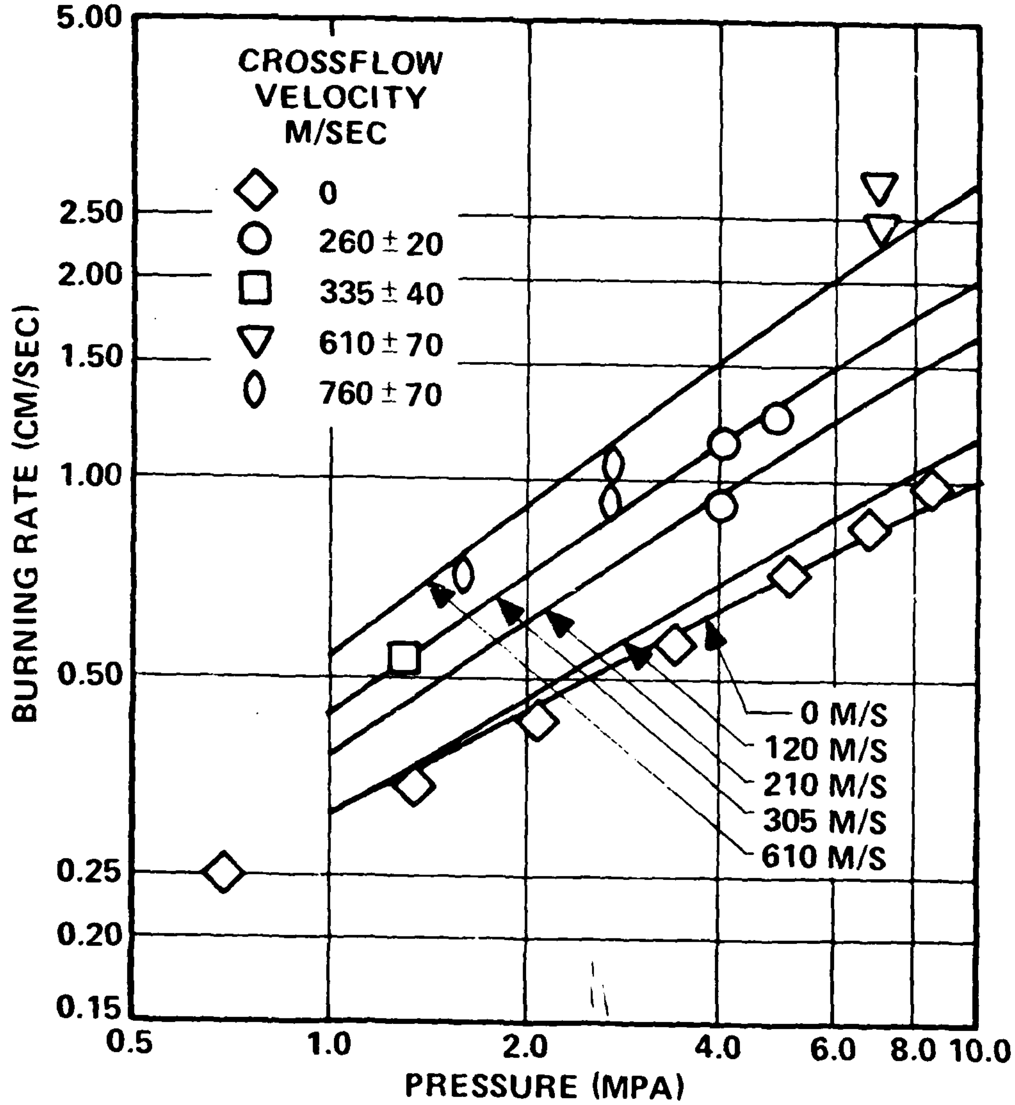
BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 5555 (82/18 AP/HTPB, 41% 1 MICRON AP, 41% 7 MICRON AP)



BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 5565 (62/18 AP/HTPB, 13.65% 90 MICRON AP, 68.35% 200 MICRON AP)



BURNING RATE PREDICTIONS (SOLID LINES) AND DATA (POINTS)
FOR FORMULATION 6626 (74/21/5 AP/HTPB/AI, 5 MICRON AI, 70% 90 MICRON A, 4% 200 MICRON AP)



CONCLUSIONS

EROSION SENSITIVITY IS FUNCTION OF:

- NO CROSS-FLOW BURN RATE
- PRESSURE

EXAMPLE: FORMULATIONS 4525, 5565, AND 6626 ARE DIFFERENT BUT HAVE SAME BASE BURN RATE AND VERY SIMILAR SENSITIVITY TO CROSS FLOW.

NOZZLELESS PERFORMANCE PROGRAM
(NPP)

SCHEDULE

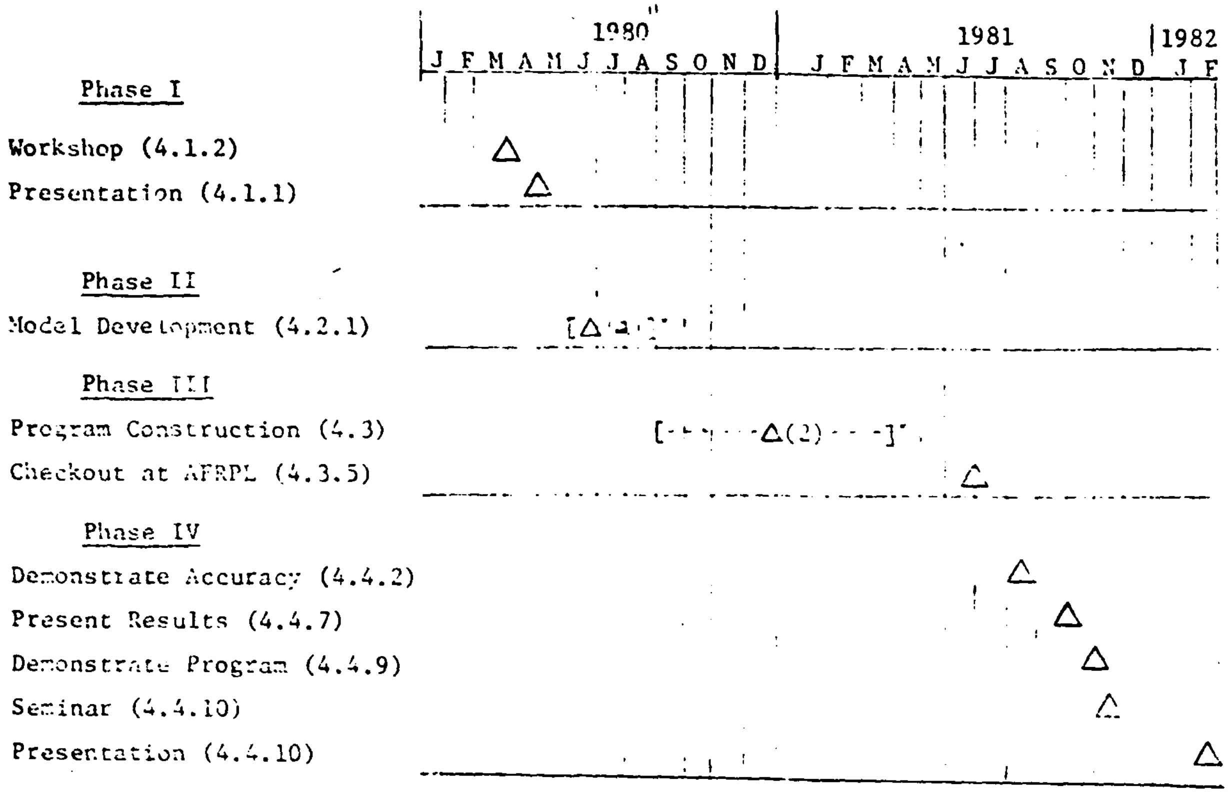
Table 1. SCHEDULE - SECTION 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Phase I - 4.1 Literature Review and Assessment																															
4.1.1 Literature Survey Assessment & Selection	△	△																													
Presentation				△																											
4.1.2 Workshop			△																												
4.1.3 Interim Report - Draft Final													△			△															
Phase II - Model Formulation and Development																															
4.2.1 Coordination & Analysis of Integration					△				△																						
4.2.2 Gas Dynamics					△			△																							
4.2.3 Erosive					△			△																							
4.2.4 Grain Deflection																															
4.2.5 Combustion Efficiency																															
4.2.6 Two Phase Flow																															
CO Approval								△																							
4.2.7 L* Instability						△		△																							
4.2.8 Assess Optional Technical Elements					△			△																							
Phase III - Program Development																															
4.3.1 Programming of Selected Models								△																							
4.3.2 Construct Program									△							△															
Output Format Approval																	△														
4.3.3 User Related Items														△		△															
4.3.4 Plots																△															
4.3.5 Integration and Checkout at AFRPL																	△	△													
Phase IV - Verification and Validation																															
4.4.1 Diagnostic Evaluation and Correction of Formulation and Programming Errors																			△												
4.4.2 Validate and Demonstrate Accuracy of 4 Motors																			△	△											
Test Matrix for CO Approval																		△													

Table 1. SCHEDULE - SECTION 2

hase IV - (cont'd)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
4.4.3	Demo. Individual and Collective Execution																			△												
4.4.4	Conduct Sensitivity Analysis and Assess Accuracy																			△	△											
4.4.5	Demo. Plotting Capability																				△											
4.4.6	Select 3 Additional Motors for Validation																				△											
	CO Approval																			△												
	Eval. Accuracy and Correct Model																					△										
	Prepare User's Manual																					△										
	Submit Draft - Publish Final (PCO)																						△									
4.4.7	Present Results to AFRPL																					△										
4.4.8	Use AFRPL Plotters																					△										
4.4.9	Formulate Acceptance Criteria																					△	△									
	CO Approval																						△									
	Demonstrate Program at AFRPL																						△									
	End of Technical Effort																						△									
4.4.10	Conduct Seminar																															
	Industry Evaluation																							△		△						
	Compile Results and Evaluate Suggested Changes																									△						
	Present at AFRPL																										△					
	Final Report - Draft																							△								
	Publish (PCO)																										△					

Table 1 - MEETING SCHEDULE SECTION 4



* Coordination and Integration Meetings as required at SEA and AFRPL.

B-1 d

JANNAF

PERFORMANCE STANDARDIZATION

SUBCOMMITTEE

ANNUAL REPORT--1979

DAWEEL GEORGE

CHAIRMAN

PSS SPECIFIC OBJECTIVES

1978-79

- ESTABLISH POSITION ON SI UNITS
- CONTINUE DEVELOPMENT OF SOLID PERFORMANCE METHODOLOGY
- ESTABLISH BURNRATE DETERMINATION METHODOLOGY

1979-80

- INITIATE PERFORMANCE PROCEDURES FOR NOZZLELESS MOTORS
- DETERMINE SPIN EFFECTS ON MOTOR PERFORMANCE
- ESTABLISH PROCEDURE FOR EXPENDED INERTS EFFECT ON PERFORMANCE

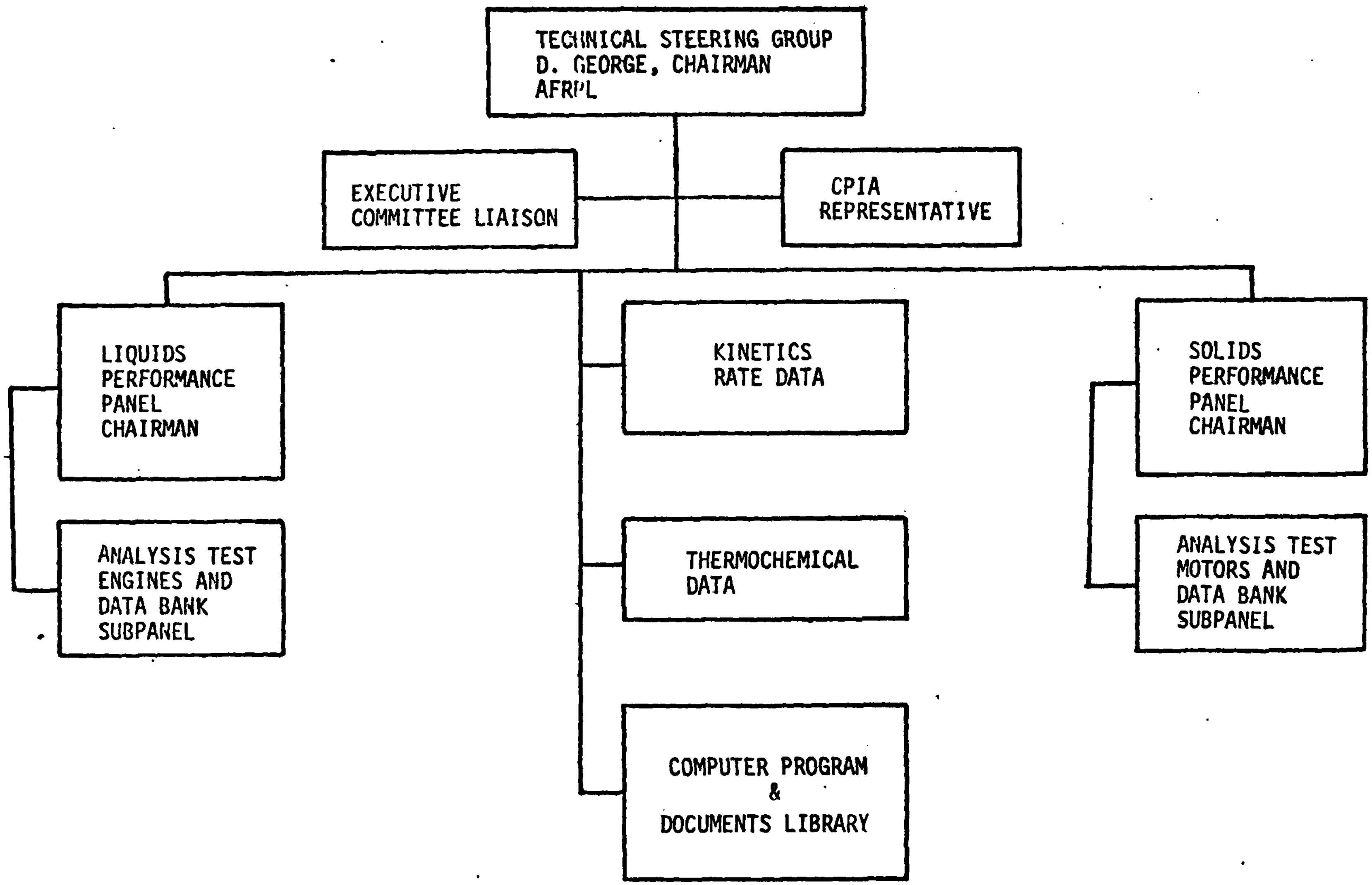


Fig.1. PERFORMANCE STANDARDIZATION SUBCOMMITTEE ORGANIZATION

ACCOMPLISHMENTS

- SI UNITS RECOMMENDATIONS SUBMITTED
- DEVELOPMENT OF SOLID PERFORMANCE METHODOLOGY PROGRESSED
- BURNRATE DETERMINATION METHODOLOGY ESTABLISHED

SOLID PERFORMANCE METHODOLOGY

IMPROVED SOLID PERFORMANCE PROGRAM

- TECHNICAL ELEMENTS
  - ADVANCED TRANSONIC ANALYSIS
  - IMPROVED APPROXIMATE TRANSONIC ANALYSIS
  - PARTICLE SIZE MODEL
  - COMBUSTION EFFICIENCY MODEL
  - PARTICLE DRAG LAW
  - THROAT EROSION MODEL
  - IMPROVED PARTICLE IMPINGEMENT
  - TD2P IMPROVED ACCURACY AND NUMERICAL TECHNIQUES
- UTILITY
  - REACTANTS LIBRARY AND PLOTTED OUTPUT

KINETICS STUDY--REACTION RATE SCREENING

- ACCURATE PERFORMANCE AT REDUCED RUN TIME

ANNUAL MEETING--JAN 79

AGENDA TOPICS:

- STATUS REPORTS
  - IMPROVED SOLID PERFORMANCE PROGRAM
  - ONE-DIMENSIONAL THREE-PHASE FLOW
- THERMOCHEMICAL AND KINETIC RATE DATA
- INTERNAL BALLISTICS
  - MOTOR BURN RATE DETERMINATION
  - SPIN EFFECTS ON BURN RATE AND PERFORMANCE
  - EXPENDED INERTS
- REFERENCE EFFICIENCY CALCULATIONS
- NOZZLELESS MOTOR PERFORMANCE
- PERFORMANCE INSTRUMENTATION

PRESENTATIONS AND PUBLICATIONS

PRESENTATION

- SOLID PROPELLANT ROCKET MOTOR PERFORMANCE PREDICTIONS USING THE IMPROVED SPP COMPUTER MODEL
  - 16TH JANNAF COMBUSTION MEETING, SEP 1979

PUBLICATION

- 12TH PSS MEETING MINUTES

CURRENT TASK AREAS

- IMPROVED SOLID PERFORMANCE PROGRAM	1980
- PERFORMANCE LOSS DUE TO SPIN EFFECTS	1980
- THERMO DATA UPDATING METHOD	1982
- TWO-PHASE FLOW, MASS TRANSFER & KINETICS CALCULATIONS	1980
- EXPENDED INERTS PROCEDURE	1981
- NOZZLELESS PERFORMANCE PROCEDURE	1982

PLANNED ACTIVITIES

WORKSHOPS

- REFERENCE EFFICIENCY CALCULATIONS (DEC 79)
- PERFORMANCE OF SPIN MOTORS (~~SPRING~~ FALL 80)
  (COSPONSOR WITH COMBUSTION SUBCOMMITTEE)

MEETING

- ANNUAL MEETING (FEB 80)

PRESENTATION

- JANNAF PROPULSION MEETING (MAR 80)

AD-A089 831 JOHNS HOPKINS UNIV LAUREL MD CHEMICAL PROPULSION INF--ETC F/G 21/8.2
JANNAF PERFORMANCE STANDARDIZATION SUBCOMMITTEE, 13TH MEETING M--ETC(U)
JUL 80 H F HEGE N00024-78-C-5384
UNCLASSIFIED CPIA-PUB-321 NL

4 of 4

END
DATE
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11-80
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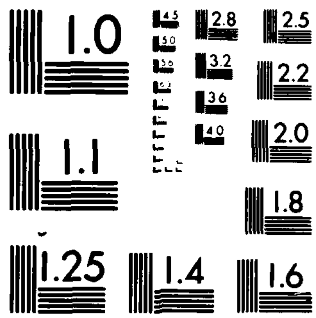
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

PERFORMANCE STANDARDIZATION SUBCOMMITTEE

13TH MEETING

SACRAMENTO, CA

14-15 FEBRUARY 1980

EFFICIENCY DEFINITIONS

D.E. COATS
SOFTWARE AND ENGINEERING ASSOCIATES, INC.
354 BROOKHOLLOW DRIVE
SANTA 'NA, CA 92705
(714) 751-3242

DEFINITIONS

$$\eta_{LOSS} = \frac{I_{SP_{TH}} - \Delta I_{SP_{LOSS}}}{I_{SP_{TH}}}$$

$$\Delta I_{SP_A} = I_{SP_{ABCD}} - I_{SP_{BCD}} = (1-\eta_A) I_{sp_{th}}$$

$$\eta_A = I_{sp_{ABCD}} / I_{sp_{BCD}}$$

KINETIC LOSS

$$\Delta I_{SP_{KIN}} = I_{SP_{RE}} - I_{SP_{ODK}} + \beta\left(I_{SP_{TH}} - I_{SP_{RE}}\right)$$

$$\Delta I_{SP_{KIN}} = I_{SP_{TH}} - \underbrace{I_{SP_{\substack{OD3P\\KIN\\MT\\2\phi}}}}_{\text{must be consistant}} + \left(I_{SP_{\substack{OD3P\\FROZ\\2\phi}}} - I_{SP_{\substack{OD3P\\FROZ\\EGPM}}}\right)$$

TWO-DIMENSIONAL-TWO PHASE FLOW LOSS

$$\Delta I_{SP_{2D2\phi}} = I_{SP_{\substack{TD2P\\RGE\\MT}}} - I_{SP_{\substack{ID\\EGPM\\MT\\RGE}}} = \left(1 - I_{SP_{TD2P}} / I_{SP_{\substack{ID\\EGPM\\RGE\\MT}}}\right) I_{SP_{th}}$$

COMBUSTION LOSS

$$\Delta I_{SP_{CE}} = I_{SP_{TH}} - I'_{SP_{TH}}(\bar{F})$$

EXPENDED INERTS LOSS

$$\Delta I_{SP_{IN}} = I_{SP_{TH}} - \left(I_{SP_{TH}} W_P + I_{SP_{IN}} W_{IN}\right) / \left(W_P + W_{IN}\right)$$

$$\Delta I_{SP_{IN}} = I_{SP_{TH}} - I_{SP_{TH}} \quad \text{(INCLUDES INERTS BASED ON } W_{IN} / W_P\text{)}$$

PREDICTION OF NOZZLE BOUNDARY LAYERS USING AEROTHERM'S "MEIT" CODE

BY

MARK SALITA

Thiokol / WASATCH DIVISION

A DIVISION OF THIOKOL CORPORATION

P O Box 524, Brigham City, Utah 84302 801/863-3511

MEIT . . . MOMENTUM/ENERGY INTEGRAL TECHNIQUE

- REFERENCE: MEIT USER'S MANUAL
  - KWONG/SUCHSLAND/TONG
  - AFRPL-TR-78-53 (ACUREX UM-78-86)
  - JULY 1978
- MEIT IS A NUMERICAL SOLUTION TO THE INTEGRAL BOUNDARY LAYER EQUATIONS THAT ATTEMPTS TO ACCOUNT FOR:
  - MASS INJECTION
  - WALL ROUGHNESS
  - CHEMICALLY-REACTING FLOW
  - LAMINAR/TRANSITIONAL/TURBULENT NATURE
  - PRESSURE GRADIENT EFFECT

Thiokol/WASATCH DIVISION

IMPROVEMENTS TO MEIT MADE BY THIOKOL

- NUMBER OF CODING ERRORS CORRECTED
- ADDITIONAL INPUT CAPABILITIES INCORPORATED
    - SPECIFIED INITIAL CONDITIONS
    - SPECIFY EDGE TEMPERATURE OR ENTHALPY
- ADIABATIC - WALL OPTION ADDED
- APPROXIMATE CLOSED - FORM SOLUTION CODED
- SEVERAL ANALYTICAL CORRELATIONS PRINTED

Thiokol/WASATCH DIVISION

GOVERNING BOUNDARY LAYER EQUATIONS

- FLOW ASSUMPTIONS
  - STEADY
  - AXISYMMETRIC
  - THIN BL
  - CHEMICALLY REACTING
  - CALORICALLY IMPERFECT
  - TURBULENT OR LAMINAR
- THE RESULTING PDEs VALID IN BOUNDARY LAYER ARE PRESENTED IN BLIMP
- MAKE THE FURTHER APPROXIMATIONS
  - UNIFORM EDDY DIFFUSIVITY
  - UNIFORM DIFFUSION COEFFICIENTS
  - NEGLIGIBLE THERMAL DIFFUSION
  - NEGLIGIBLE RADIATION FLUX
  - UNITY LEWIS NUMBER
- INTEGRATING THESE EQUATIONS ACROSS THE BOUNDARY LAYER FROM WALL TO INFINITY YIELDS THE MOMENTUM AND ENERGY INTEGRAL EQUATIONS ...

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$$\boxed{\begin{aligned} &\frac{d}{ds}(\rho_e U_e^2 r_w \theta) = F(\theta) \qquad (1) \\ &\frac{d}{ds}(\rho_e U_e r_w \omega\varphi) = G(\theta,\varphi) \qquad (2) \end{aligned}}$$

$$\text{WHERE } F = \left[\frac{C_f}{2} + \frac{\rho_w v_w}{\rho_e U_e} + \frac{H\theta}{\rho_e U_e^2}\ \frac{d_{pe}}{ds}\right] \rho_e U_e^2\ r_w$$

$$G = \left[\frac{h_{aw} - h_w^\circ}{h_e^\circ - h_w^\circ}\ S_T + \frac{\rho_w v_w}{\rho_e U_e}\right] \rho_e U_e r_w \omega$$

$$\omega = h_e^\circ - h_w^\circ$$

$$h_{aw} = h_e + Fr \frac{U_e^2}{2}$$

$$h_w^\circ = h_w + \frac{v_w^2}{2} \doteq h_w$$

$$H = \delta^*/\theta$$

$$C_f = 2\ \tau_w/\rho_e U_e^2$$

$$S_T = \dot{q}_w/\rho_e U_e (h_{aw} - h_w^\circ)$$

THESE EQUATIONS ARE IDENTICAL TO THOSE SOLVED IN TBL EXCEPT TBL ASSUMES

- FROZEN CHEMISTRY
- NO MASS INJECTION
- DIFFERENT MODELS FOR C_f, S_T, $H \rightarrow F(\theta, \Phi)$
- NO LAMINAR/TRANSITIONAL REGION

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MODELS FOR F_r, H, C_f, S_T

$$\frac{C_f}{2} = \frac{\hat{C}_f}{2} \cdot K_3 \cdot K_5 \cdot K_7$$

$$S_T = \hat{S}_T \cdot K_4 \cdot K_6 \cdot K_8$$

PARAMETER		MEIT*	TBL
RECOV FACTOR	F_r	$Pr^{1/3}$	$Pr^{1/3}$
SHAPE FACTOR	H	$f\left(\frac{T_w}{T_e}, Re_\theta\right)$	$f\left(\frac{h_w}{h_e}, \frac{\delta_u}{\delta_T}, \frac{U_e^2}{2\,h_c}\right)$
INCOMPRESS SKIN FRICT	$\hat{C}_f$	$f\,(Re_\theta, \beta)$	$f\left(Re_\theta, \frac{U_e^2}{2\,hc}\right)$
INCOMPRESS STANTON	$\hat{S}_T$	$f\,(Re_\theta, \beta, Pr)$	$f\,(Re_\Phi, Re_\theta, Pr)$
COMPRESS FACTOR	K_3, K_4	$f\left(\frac{T_e}{T_{ref}}, h_{ref}\right)$	$f\left(\frac{T_e}{T_{aw}}, \frac{T_s}{T_{aw}}\right)$
ROUGH FACTOR	K_5, K_6	$f\left(\frac{h_{rough}}{\theta}, \psi\right)$	1.0
TRANSPIR FACTOR	K_7, K_8	$f\,(B'\,R', RAF)\,Pr$	1.0

*ONLY TURBULENT MODELS ARE SHOWN HERE

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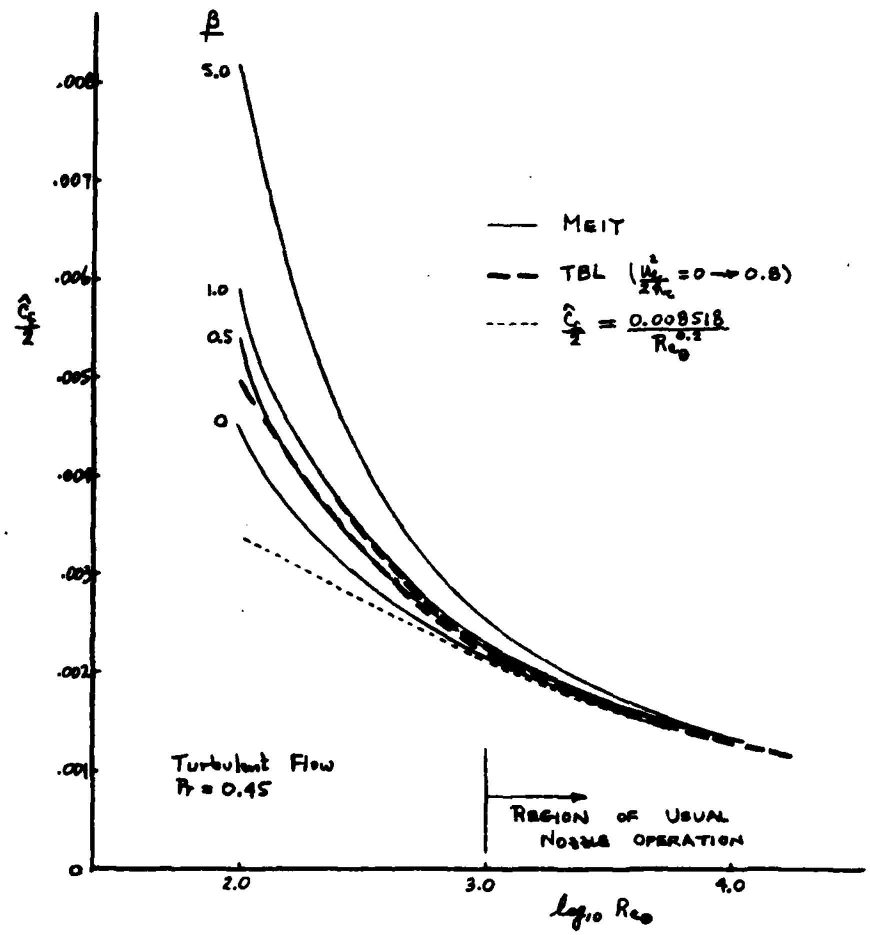
INFORMATION ON THIS PAGE WAS PREPARED TO SUPPORT AN ORAL PRESENTATION AND CANNOT BE CONSIDERED COMPLETE WITHOUT THE ORAL DISCUSSION.

COMPARISON OF MODELS FOR $\hat{C}_f$

MEIT vs TBL

(Perfect Gas Approximation)



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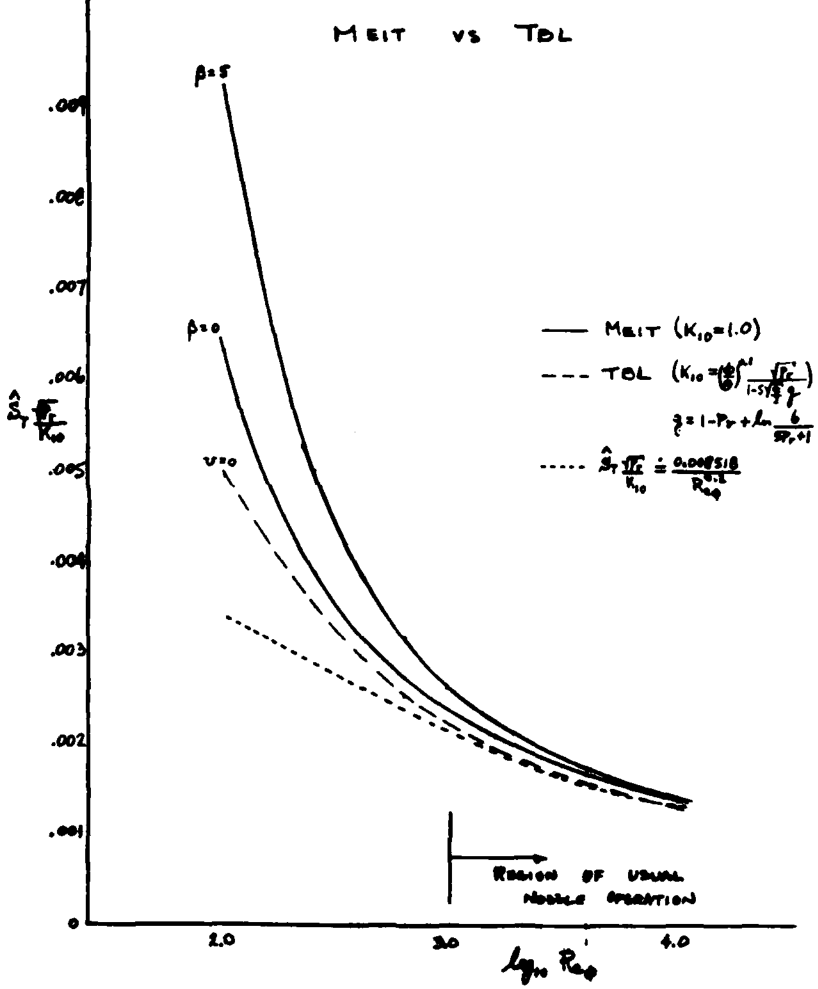
Comparison of Models for $\hat{S}_T$



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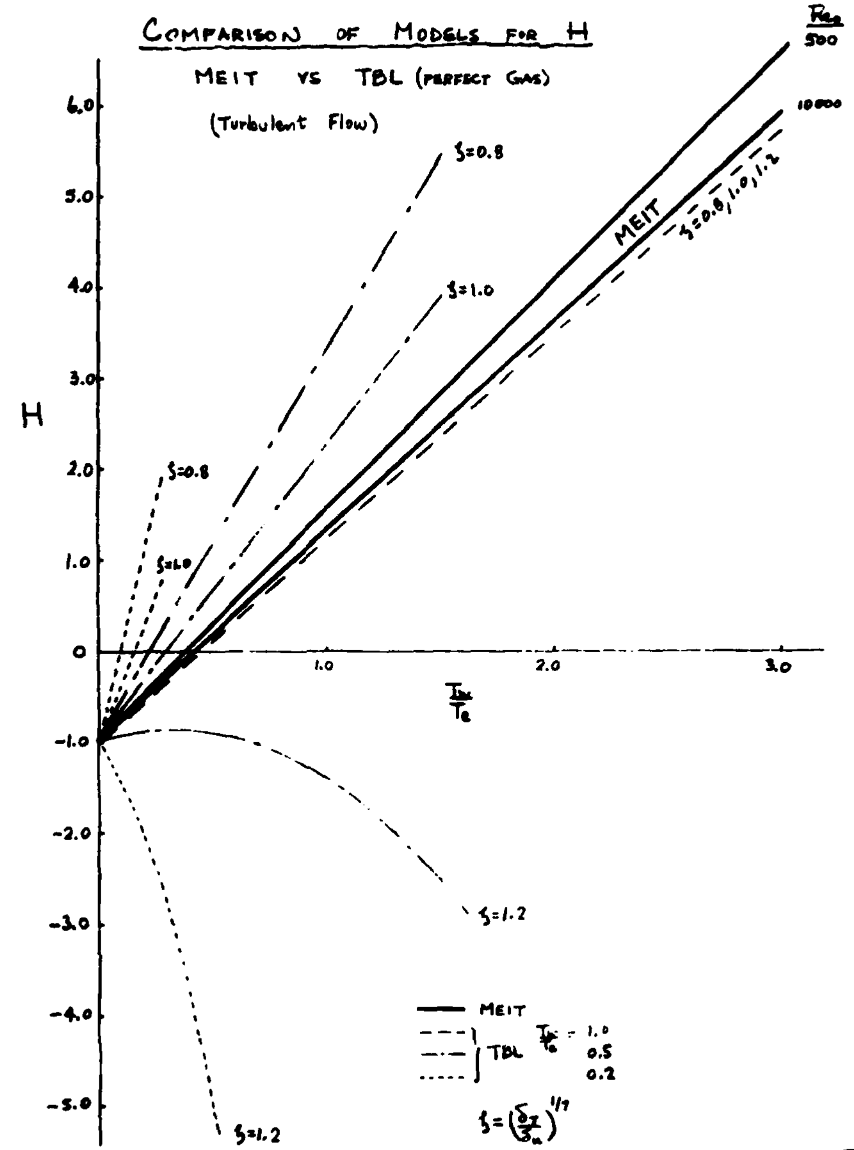

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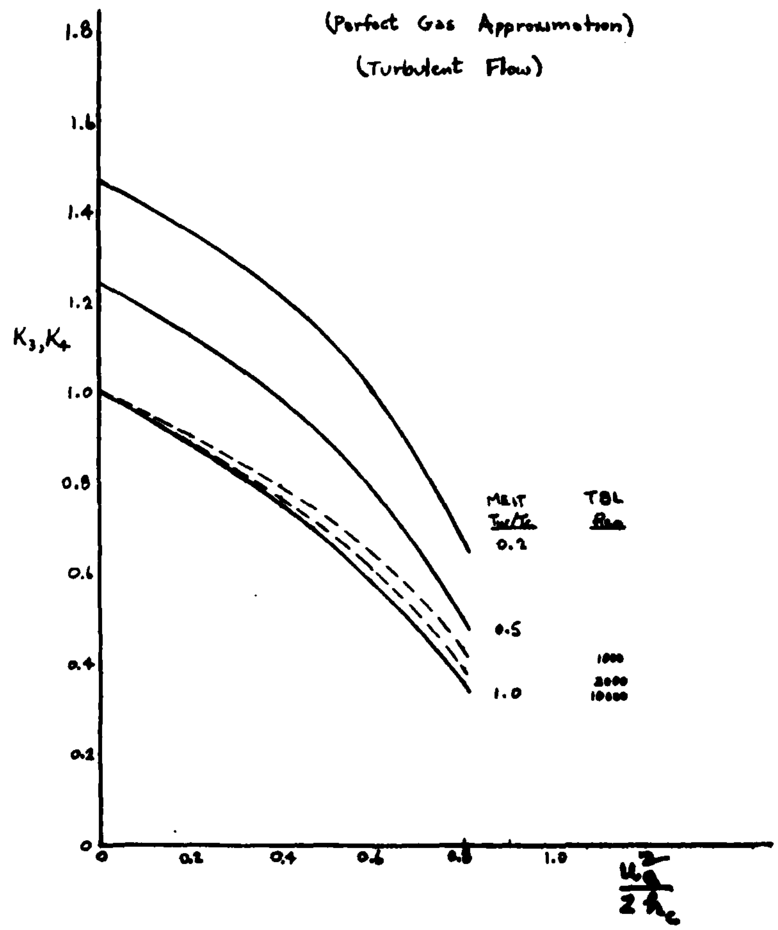
Comparison of Models for K_3, K_4

Meit vs TBL



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SOLUTION TECHNIQUES

NOW THAT MODELS FOR C_F, S_T, H, F_r ARE SPECIFIED, EQUATIONS (1, 2) REPRESENT TWO EQUATIONS FOR θ AND Φ AND MAY BE INTEGRATED...

MEIT...USING MODIFIED IMPLICIT EULER

TBL...USING 4TH - ORDER RUNGE KUTTA

APPROXIMATE CLOSED-FORM...USING VARIATION OF PARAMETERS

$$\text{LET } \frac{\hat{C}_f}{2} \doteq \frac{C}{Re_\theta^m}, \qquad \hat{S}_T \sqrt{P_r} \doteq \frac{C}{Re_\varphi^m}, \qquad H = 2.32 \frac{T_w}{T_e} - 0.96$$

$$h \doteq Cp_f T - b, \qquad \frac{T_c}{T_e} \doteq \frac{1}{1 - U_e^2/2\, Cp_f T_c}$$

THEN

$$\theta = \left[\theta_o^{1+m} + \frac{(1+m)\, CRe_x^{-m}}{(\rho_e U_e^2 r_w g_4)^{1+m}} \int_{x_o}^{x} (1 + B' R' R)(\rho_e U_e^2 r_w g_4)^{1+m} K_3 K_5 K_7 X^m \sec \alpha_w dx\right]^{\frac{1}{1+m}}$$

$$\Phi = \left[\varphi_o^{1+m} + \frac{(1+m)\, CRe_x^{-m} / \sqrt{P_r}}{(\rho_e U_e r_w \omega)^{1+m}} \int_{x_o}^{x} (C_1 + B' R')(\rho_e U_e r_w \omega)^{1+m} K_3 K_6 K_8 X^m \sec \alpha_w dx\right]^{\frac{1}{1+m}}$$

WHERE

$$g_4 = \left(\frac{U_e^2}{1 - U_e^2/2\, Cp_f T_c}\right)^{1.16 \frac{T_w}{T_c}}$$

$$c_1 = \frac{h_{aw} - h_w}{h_e^\circ - h_w}$$

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PARAMETRIC STUDIES

- EFFECT OF NOZZLE LOCATION X (FIGURES 11, 12)
- EFFECT OF WALL TEMPERATURE T_W (FIGURES 11, 12)
- EFFECT OF ROUGHNESS (FIGURE 13)
- EFFECT OF TRANSPIRATION (FIGURE 14)
- EFFECT OF INITIAL CONDITIONS (θ_0, φ_0)

CONCLUSIONS:

- GROWTH OF BL IS NEARLY LINEAR BEYOND THROAT
- T_W HAS LARGE EFFECT (FACTOR OF 5 BETWEEN COLD/HOT WALL)
- ROUGH INLET HAS NEGLIGIBLE EFFECT ON θ, S_T
- ROUGH NOZZLE INCREASES θ, φ, S_T LIKE $(\text{HEIGHT})^{1/4}$
- TRANSPIRATION INCREASES θ (INJECTED LOW - MOMENTUM DOMINATES SHEAR - REDUCTION)

  DECREASES S_T (DUE TO K_8)
- MODERATE VARIATION IN θ_0, φ_0 HAS NEGLIGIBLE EFFECT
- $\theta \sim Re_x^{-1/6} \sim p_c^{-1/6}$

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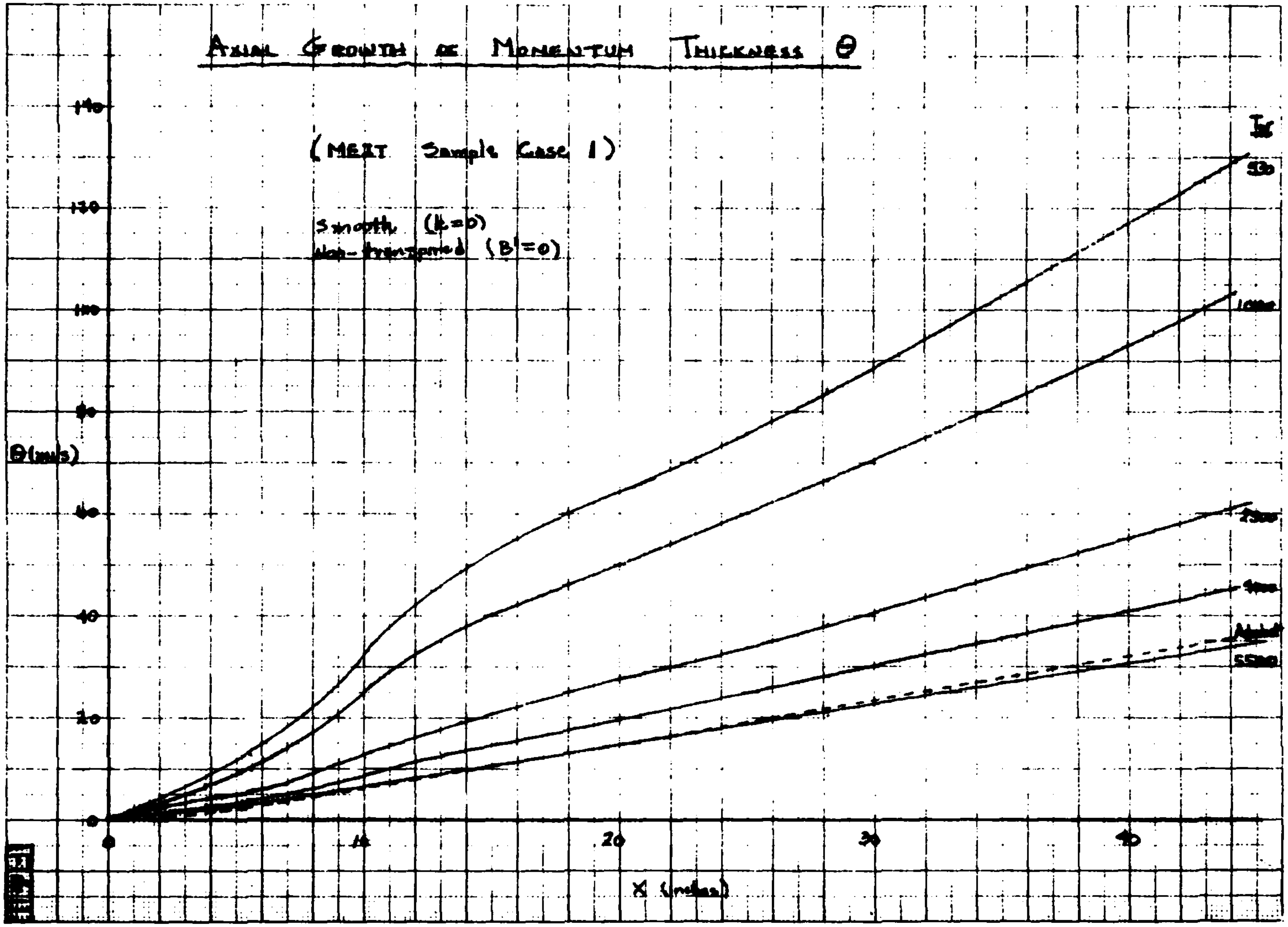

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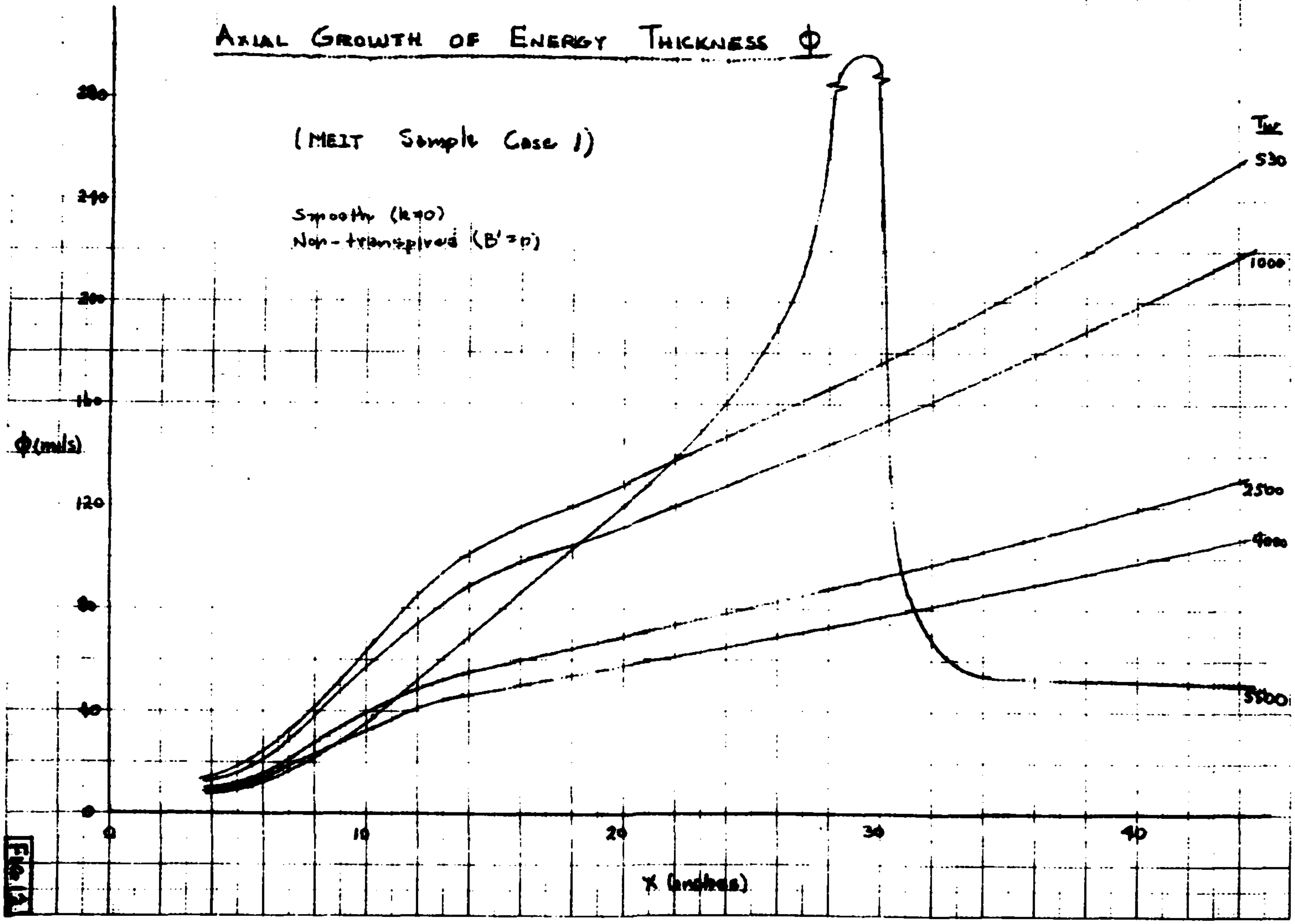

FIG. 13

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EFFECT OF TRANSPIRATION ON $\theta, \phi, \mathcal{S}_T$

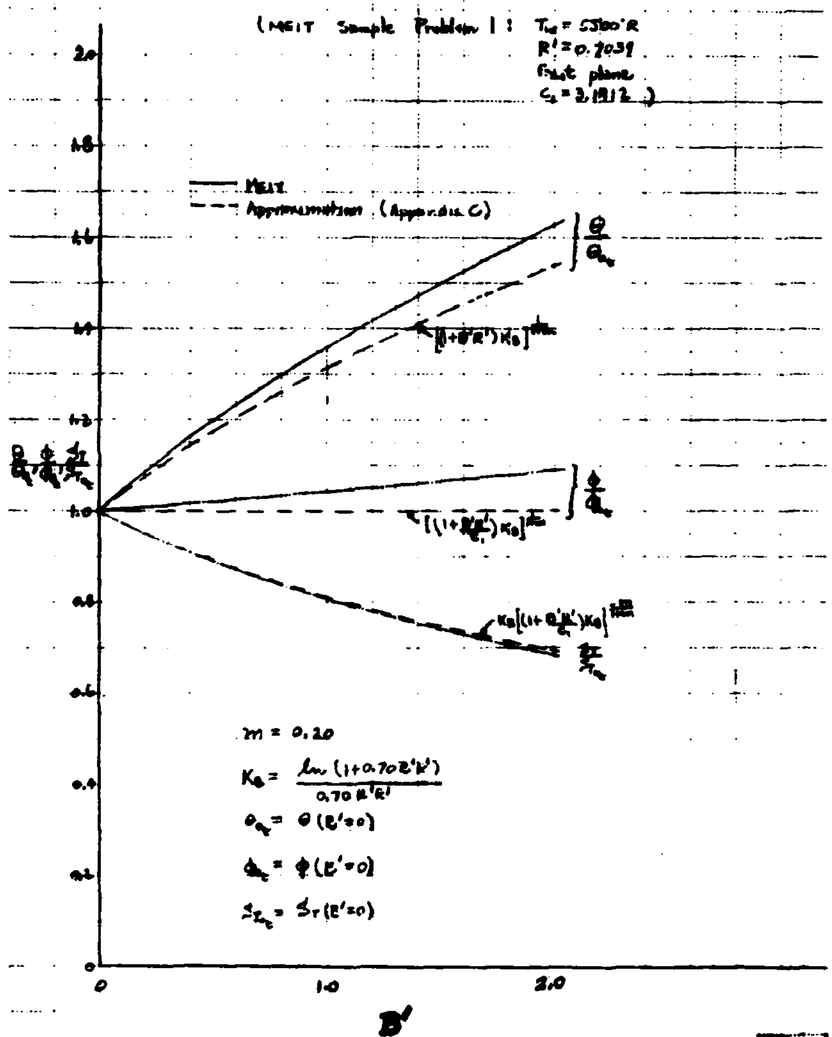

FIG 14

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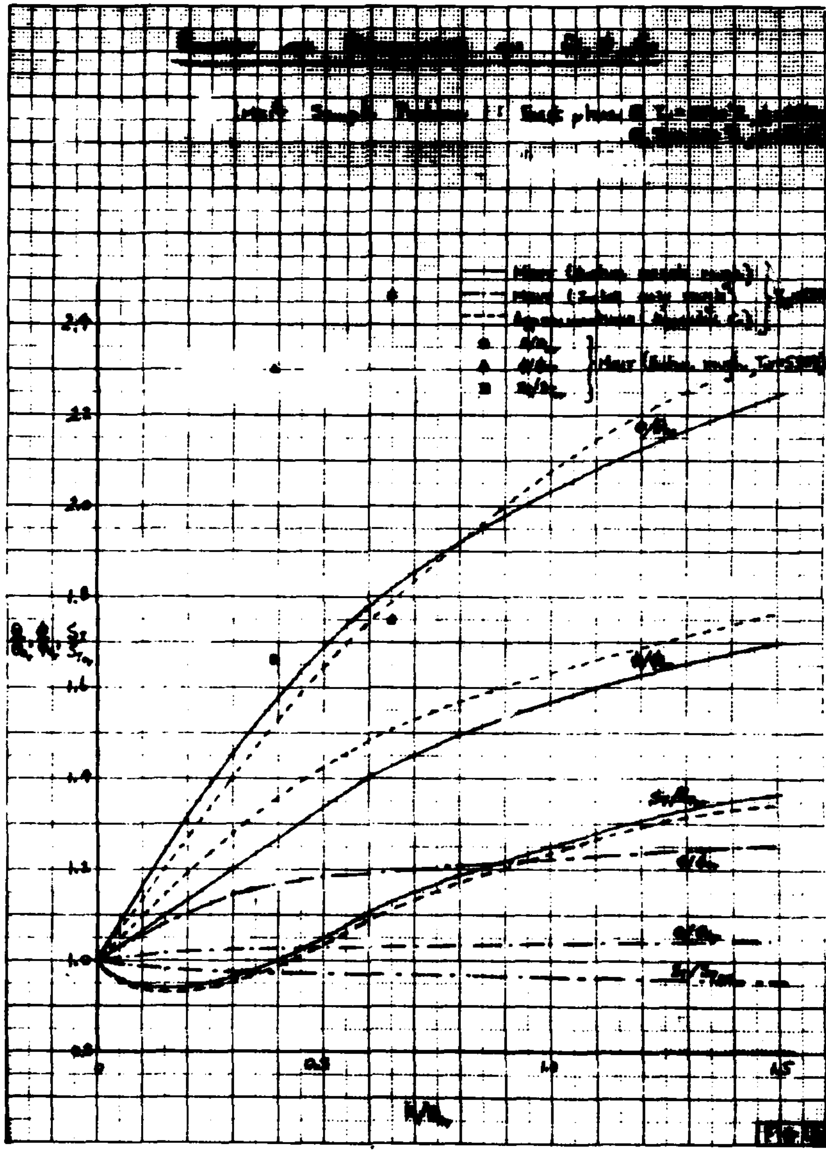

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COMPARISON OF PREDICTIONS . . . MEIT VS TBL

FOR SAMPLE PROBLEM1:

	MEIT	TBL	MEIT	TBL
T_W (°R)	530	530	5,500	5,500
θ (INCH)	0.1290	0.0610	0.0338	0.0405
Φ (INCH)	0.2551	0.0926	0.0540	0.0790
$\rho_e u_e S_T$	0.0768	0.0493	0.0476	0.0519

- WHY ARE THERE SUCH LARGE DIFFERENCES (ESPECIALLY FOR COLD WALL)?
- USING APPROXIMATE FORMS OF THE CLOSED-FORM SOLUTIONS, THE EFFECTS OF COMPRESSIBILITY, EDGE CONDITIONS, SHAPE FACTOR MODEL, AND PRANDTL NUMBER MAY BE ISOLATED AS FOLLOWS . . .

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$$\frac{(\theta)_{MEIT}}{(\theta)_{TBL}} = (f_\theta)_{COMPRESS}\,(f_\theta)_{EDGE}\,(f_\theta)_{SHAPE\ FAC}$$

$$\frac{(\rho_e u_e S_T)_{MEIT}}{(\rho_e u_e S_T)_{TBL}} = (f_{S_T})_{COMPRESS}\,(f_{S_T})_{EDGE}\,(f_{S_T})_{P_r}$$

	T_w = 530°R		T_w = 5,500°R	
	f_θ	f_{S_T}	f_θ	f_{S_T}
INCOMPRESSIBLE VALUE	1.00	0.85	1.00	0.90
COMPRESSIBILITY MODEL (K_3)	1.92	2.28	1.14	1.27
EDGE CONDITIONS (T_e, ρ_e, u_e)	1.02	0.64	0.74	0.64
SHAPE FACTOR MODEL (g_4)	1.32	--	0.81	--
PRANDTL NUMBER EFFECT (f_{Pr})	--	1.30	--	1.30
TOTAL OF ESTIMATED EFFECTS	2.59	1.61	0.68	0.95
EXACT	2.11	1.56	0.82	0.92

THUS IT MAY BE CONCLUDED THAT THE BEHAVIOR OF THE COMPRESSIBILITY FACTOR K_3 DOMINATES THE DIFFERENCE BETWEEN THE MEIT AND TBL PREDICTIONS; SPECIFICALLY, THE MODELS FOR K_3 ARE SIMILAR FOR HOT WALLS, BUT MEIT PREDICTS A STRONG EFFECT OF REDUCED WALL TEMPERATURE THAT IS NOT MODELED IN THE K_3 OF TBL.

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COMPARISON OF PREDICTIONS TO DATA

- FINAL VALIDATION OF MEIT REQUIRES AGREEMENT WITH DATA
- LIMITED NOZZLE DATA ARE AVAILABLE (CONFIGURATIONS, TEST CONDITIONS, MEASUREMENT STATIONS)
- BACK/CUFFEL (JPL) C-D NOZZLE BOUNDARY LAYER (AIAAJ 11/71, 5/72) WAS SIMULATED USING MEIT AND BLIMP:

	COLD WALL				HOT WALL			
	$C_f/2$	H	θ	$\rho_e u_e S_T$	$C_f/2$	H	θ	$\rho_e u_e S_T$
MEASURED AT X = 18.65 IN.	0.00088	-0.32	0.0380	0.0280	0.00068	7.54	0.0065	--
TBL (SPP)	0.00045	-0.29	0.0344	0.0170	WILL NOT RUN FOR $T_W > T_{aw}$			
MEIT	0.00106	2.92	0.0137	0.0351	0.00071	7.48	0.0050	0.0370
BLIMP	0.00084	1.92	0.0146	0.0181	--	--	--	--

- OBSERVATIONS
  - TBL PREDICTS θ AND H WELL, BUT $C_f/2$ POORLY, (EQUATION (1) SHOWS THIS TO BE INCONSISTENT)
  - MEIT PREDICTS
    - HOT WALL WELL
    - COLD WALL POORLY BECAUSE THE MODEL FOR SHAPE FACTOR ASSUMES EQUAL VELOCITY AND THERMAL BL THICKNESSES
  - BLIMP PREDICTS $C_f/2$ WELL BUT H AND θ POORLY

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CONCLUSIONS

- MEIT HAS BEEN EXERCISED EXTENSIVELY AT THIOKOL
- IT IS CHEAP ($2 PER RUN), VERSATILE (ROUGHNESS, TRANSPIRATION, ETC.), EASILY UNDERSTOOD
- MEIT SHOWS REASONABLE AGREEMENT WITH BACK/CUFFEL HOT-WALL DATA
- MEIT SHOWS BAD AGREEMENT WITH BACK/CUFFEL COLD-WALL DATA DUE TO INABILITY OF MODEL FOR SHAPE FACTOR TO ACCOUNT FOR DIFFERENT THERMAL AND VELOCITY BL THICKNESSES
- COMPARISONS OF MEIT TO ADDITIONAL DATA SHOULD BE MADE, AND THE MODEL FOR SHAPE FACTOR SHOULD BE IMPROVED

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UNSTEADY THREE-DIMENSIONAL FLOW IN PROPULSIVE NOZZLES

Joe D. Hoffman
Purdue University

February 1980

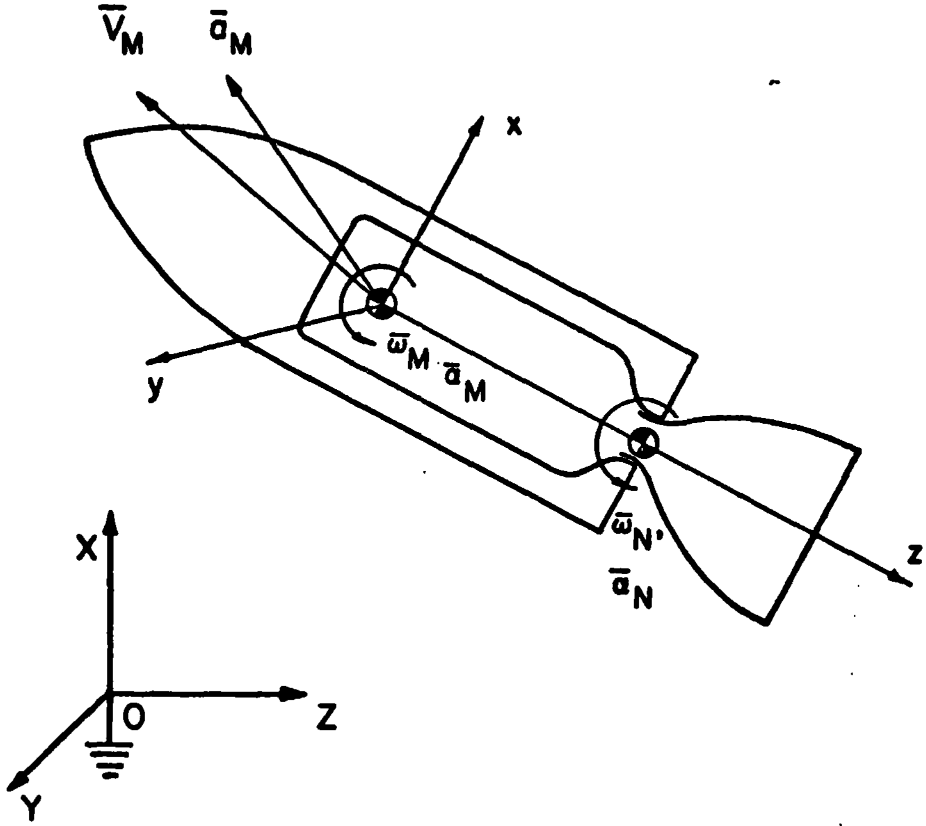
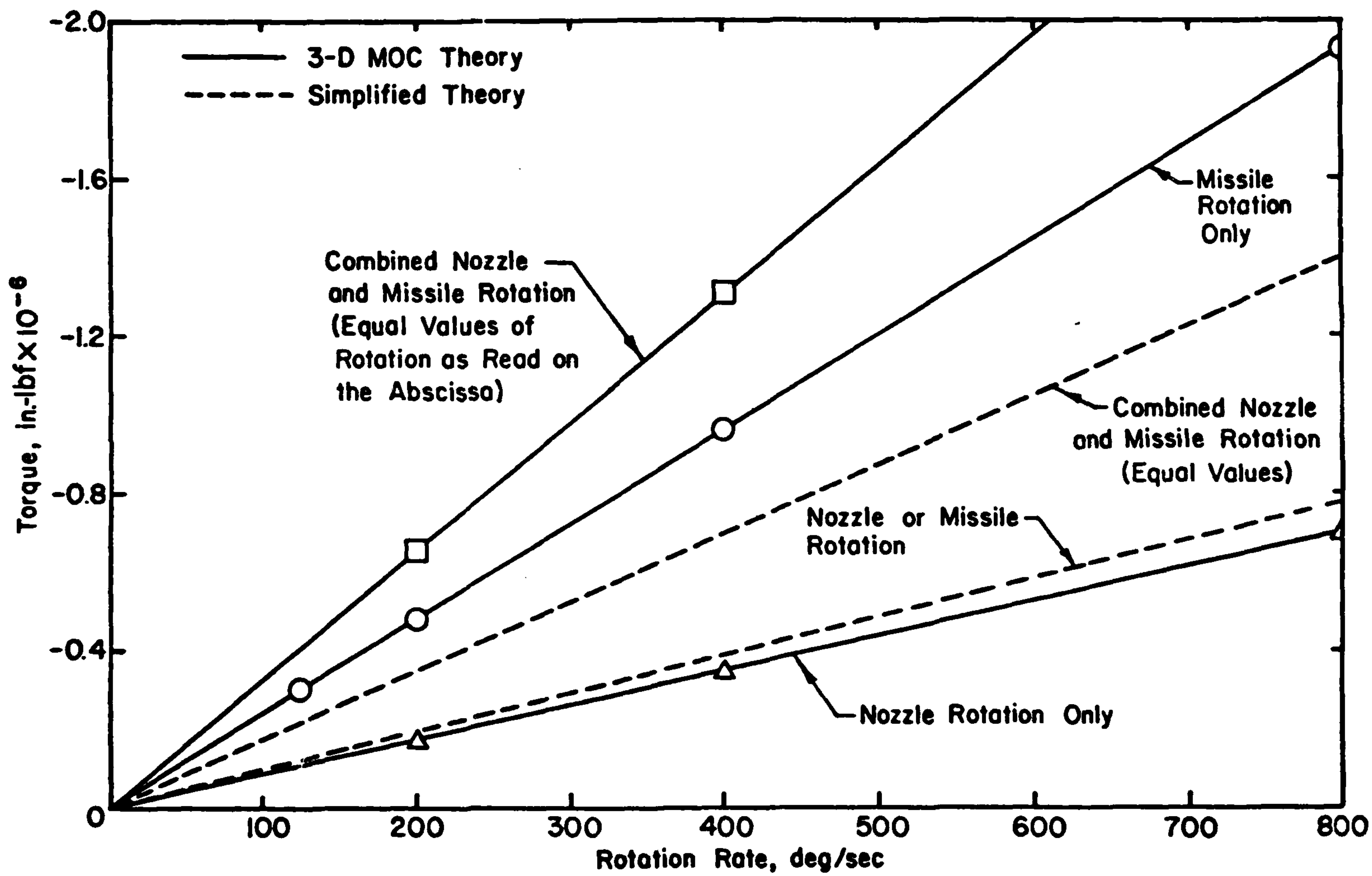


Figure 1. Physical arrangement.



(b) Combined Nozzle and Missile Rotation, Figure 2, continued.

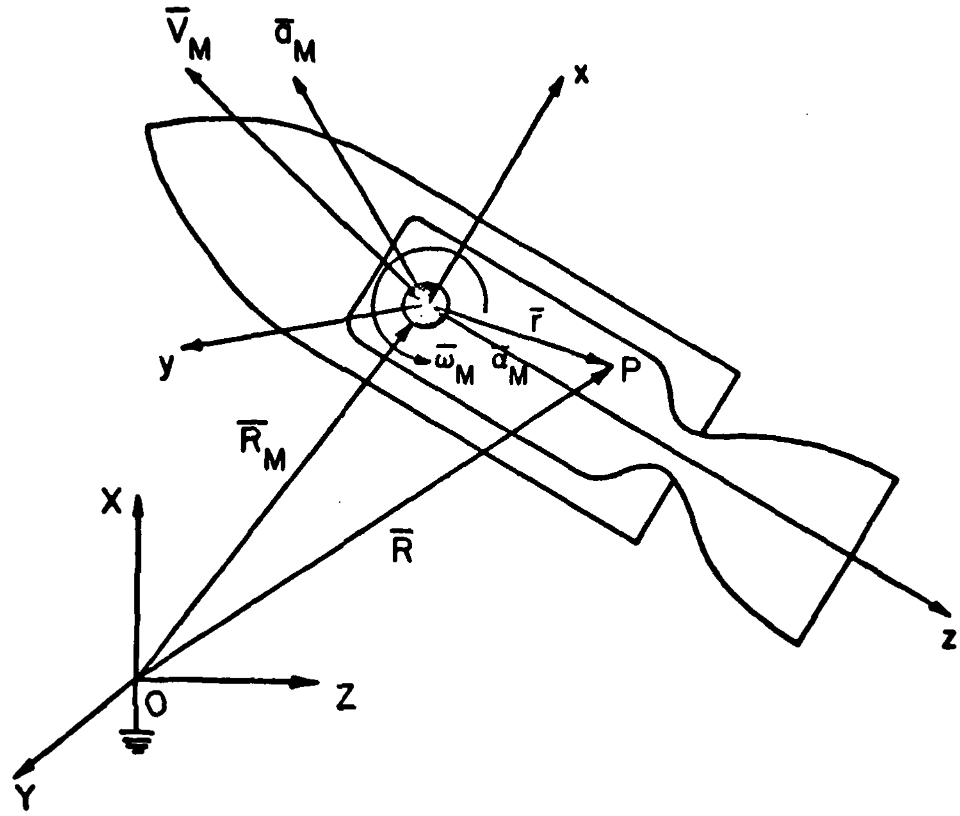


Figure 4. Physical arrangement, nonrotating nozzle.

Gas Dynamic Model

1. Isentropic (i.e., inviscid, adiabatic) flow.
2. No body forces except those due to missile rotation.
3. No condensed phases.
4. Perfect gas.
5. Frozen flow.

Method of Analysis

1. Unsteady three-dimensional flow.
2. Steady flow as limit at large time.
3. Cylindrical coordinate system.
4. Axisymmetric boundaries.
5. Transformed computational space.
6. Three-dimensional effects due to rotation only.
7. MacCormack's method at interior points.
8. Kentzer's method at all boundary points.

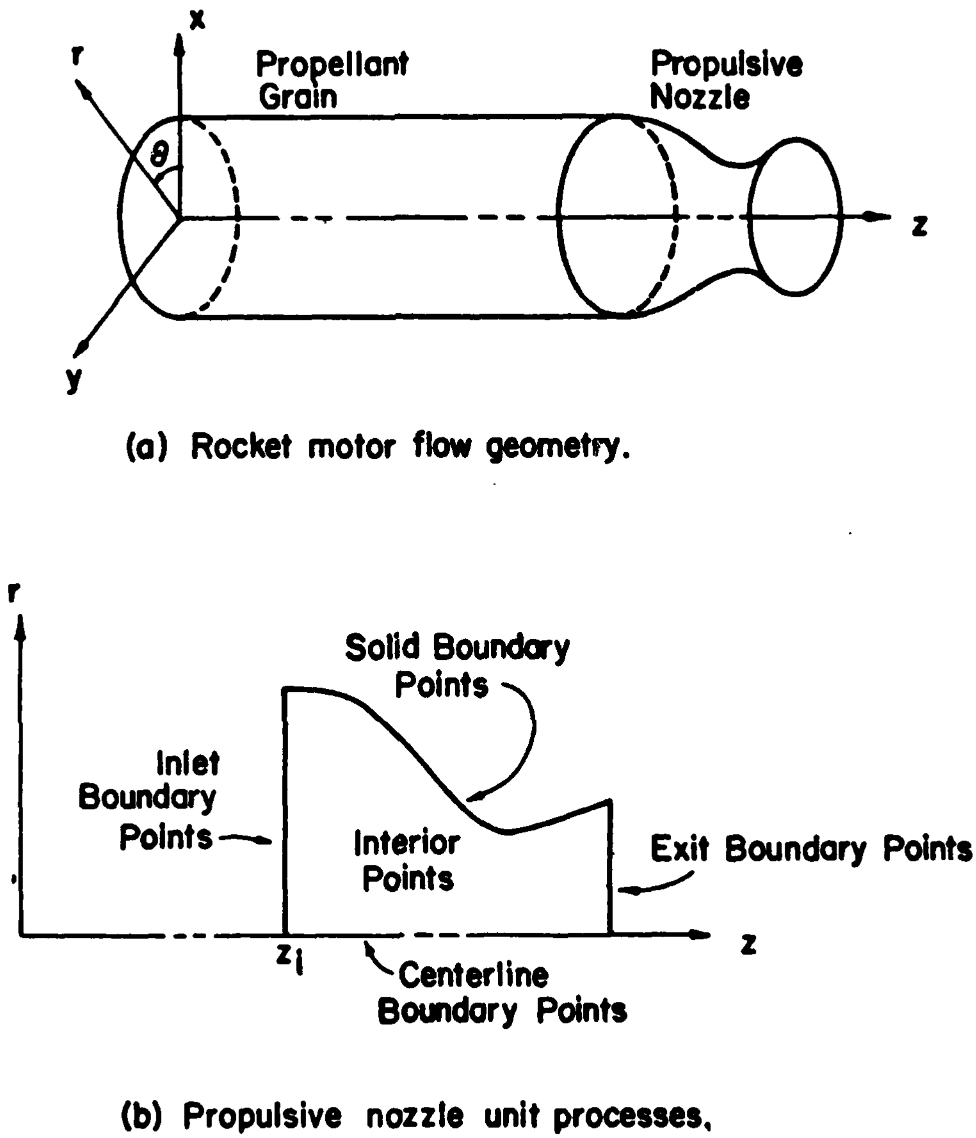
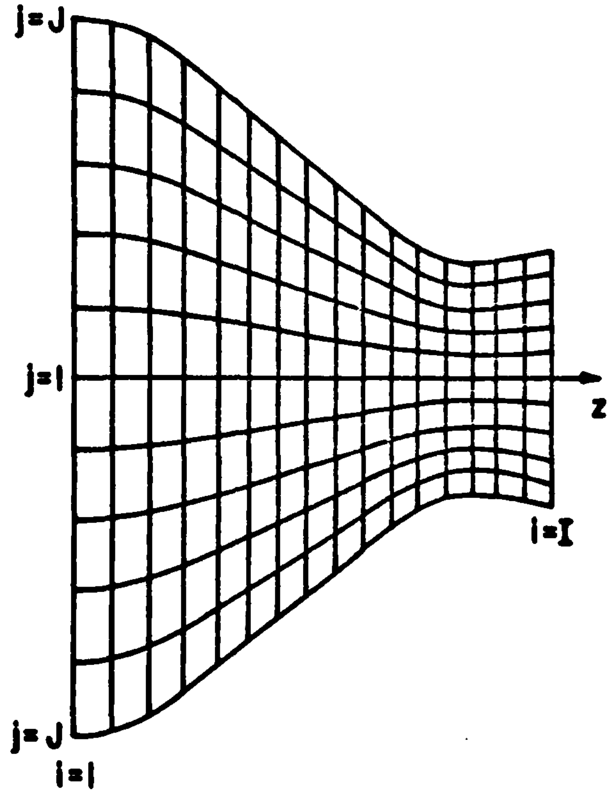
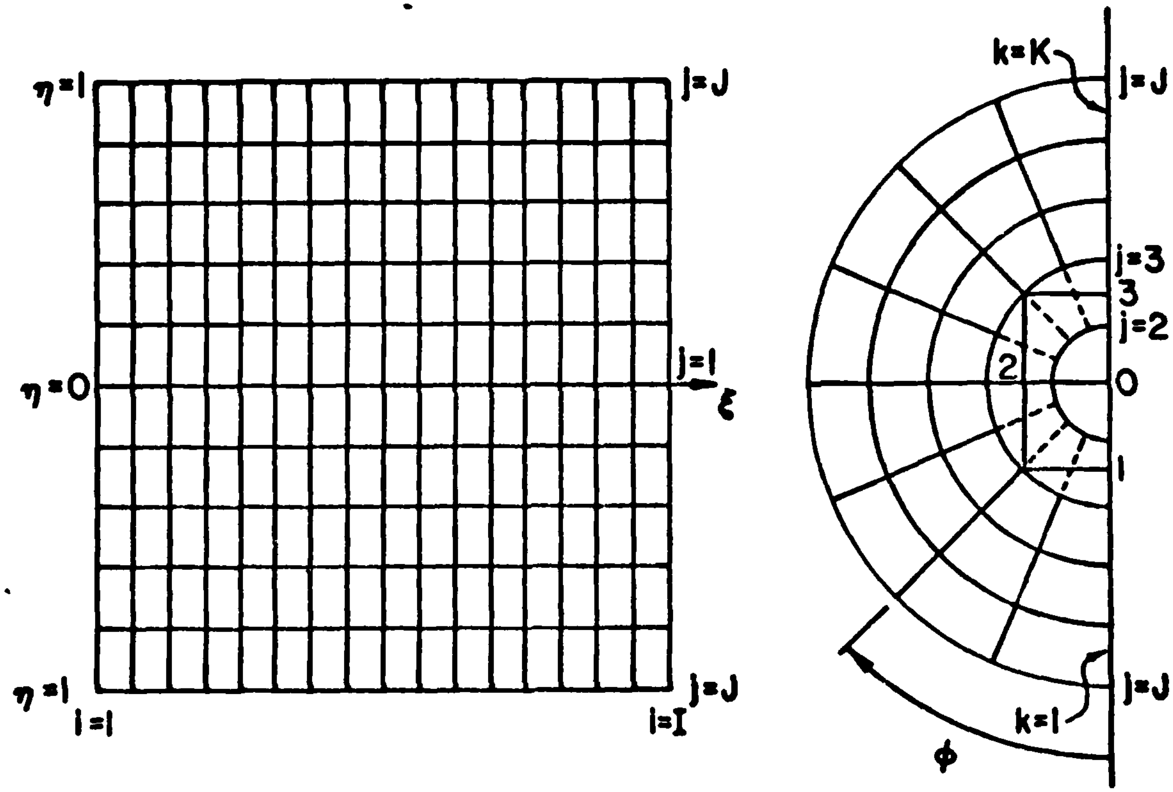


Figure 5. Flow field definition.



(a) Physical space, r-z plane.

Figure 8. Finite difference grid.



(b) Computational (η, ϕ, ξ) space.

Figure 8, continued.

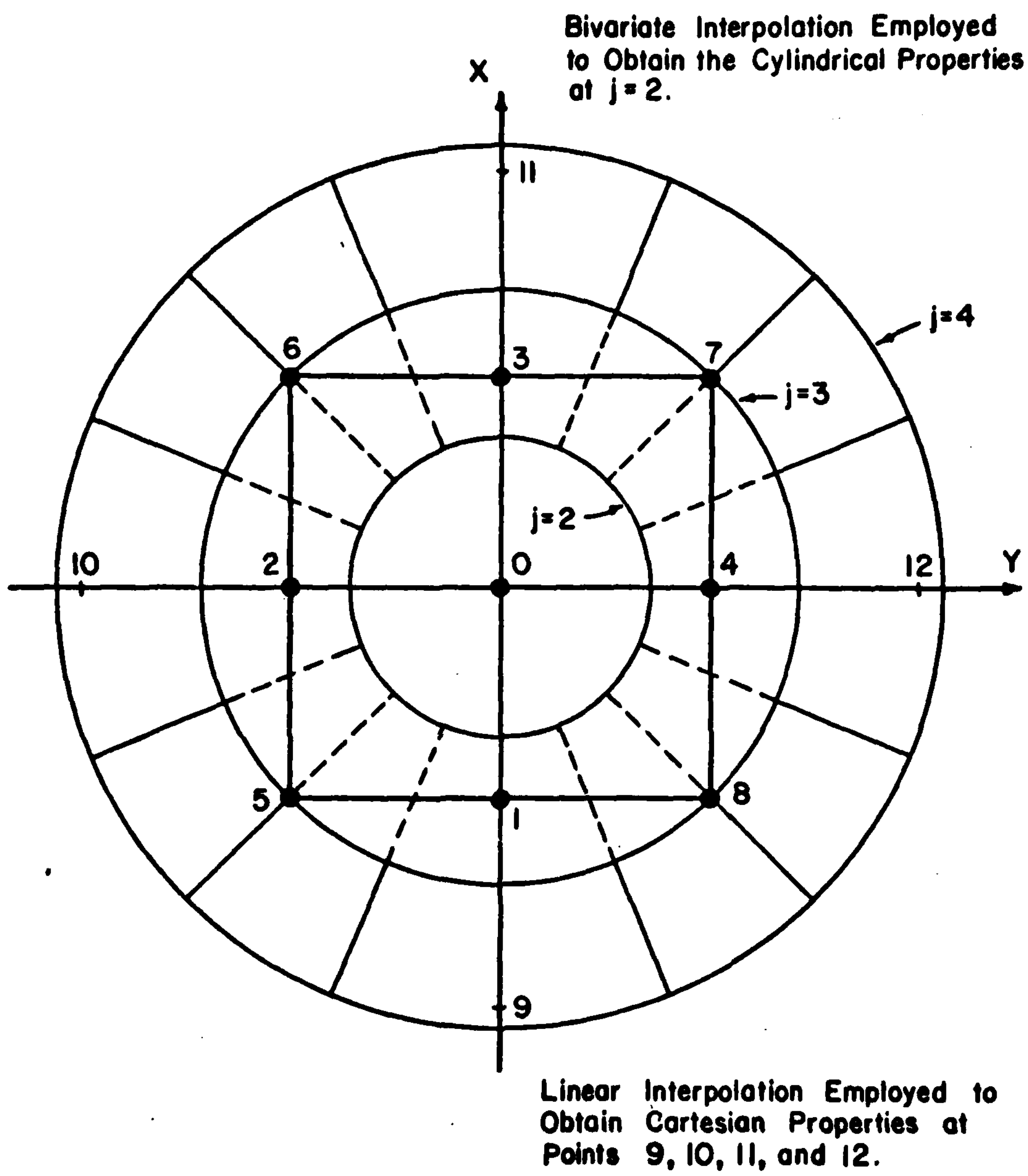


Figure 9. Cartesian grid network in the region of the centerline.

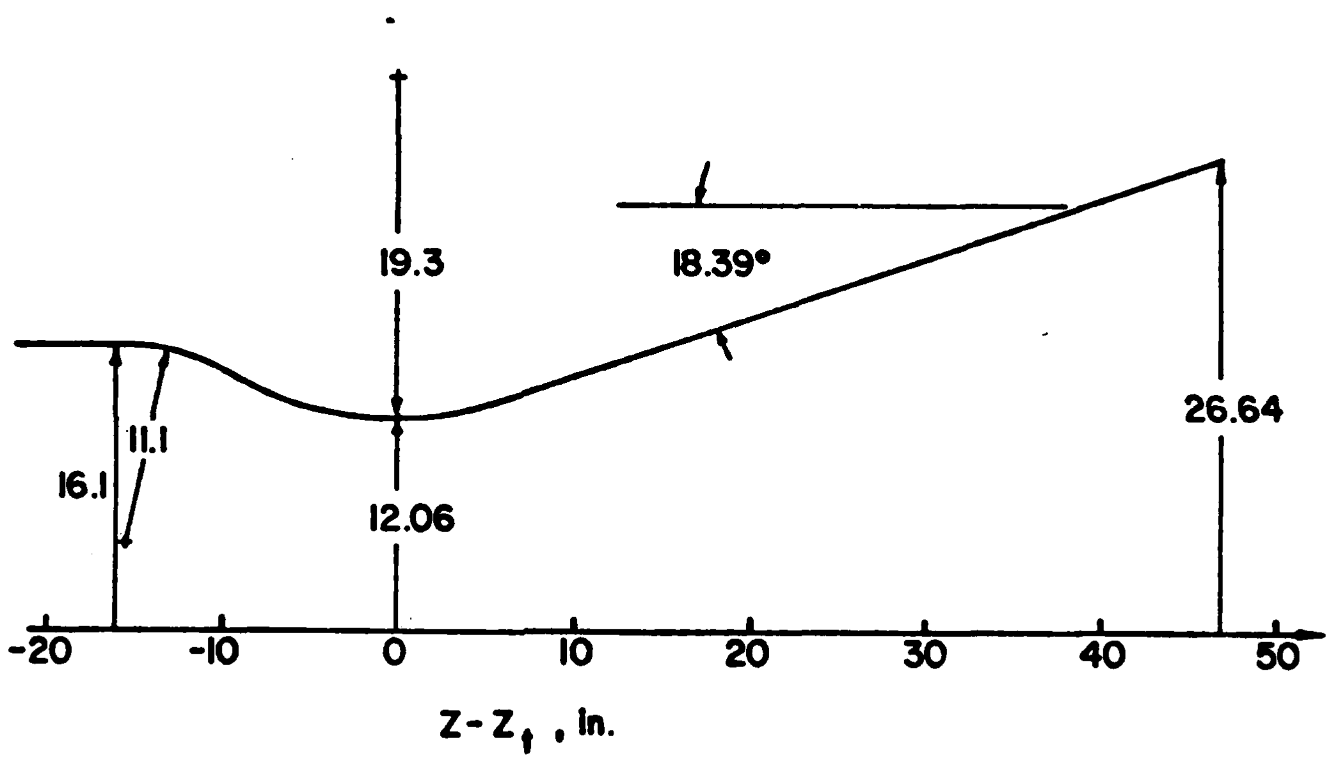
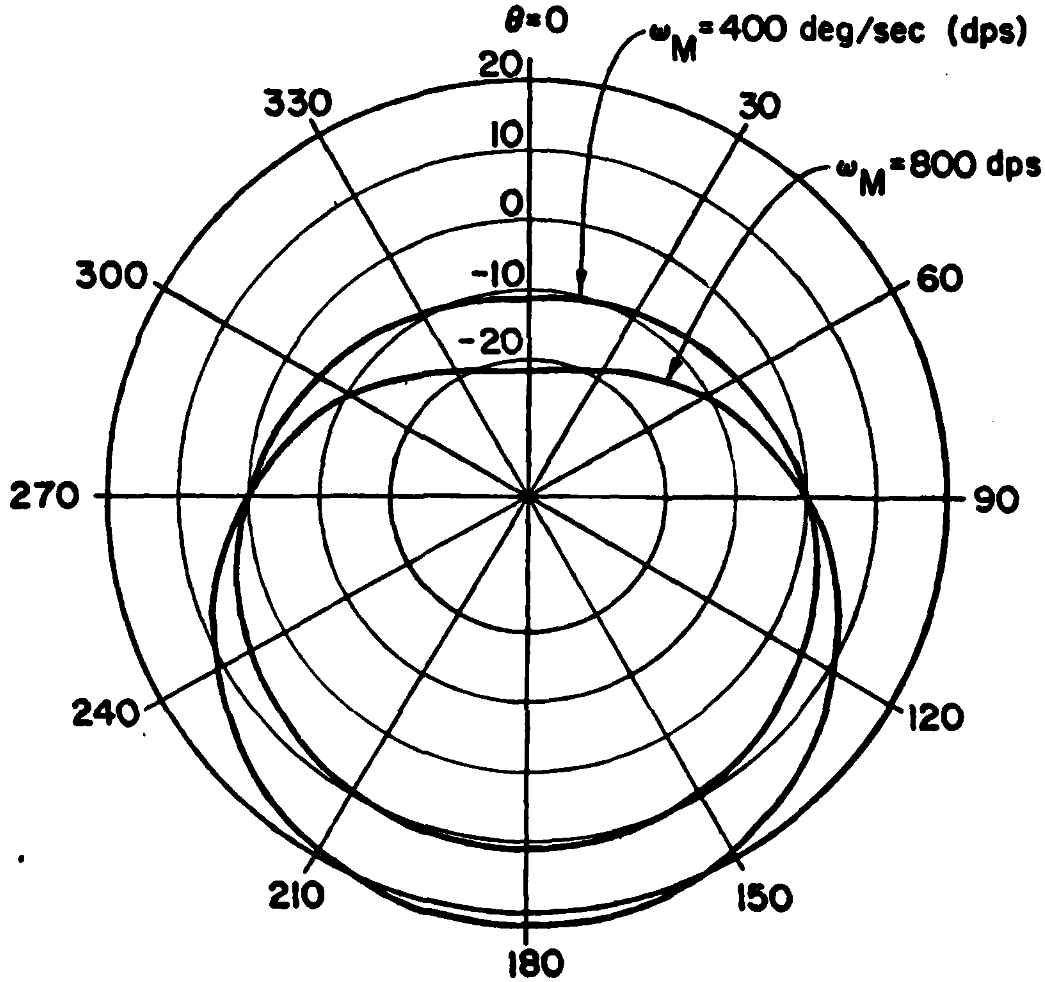


Figure 12. Propulsive nozzle rotation study geometry.

TABLE 1. Data for the nozzle studies.

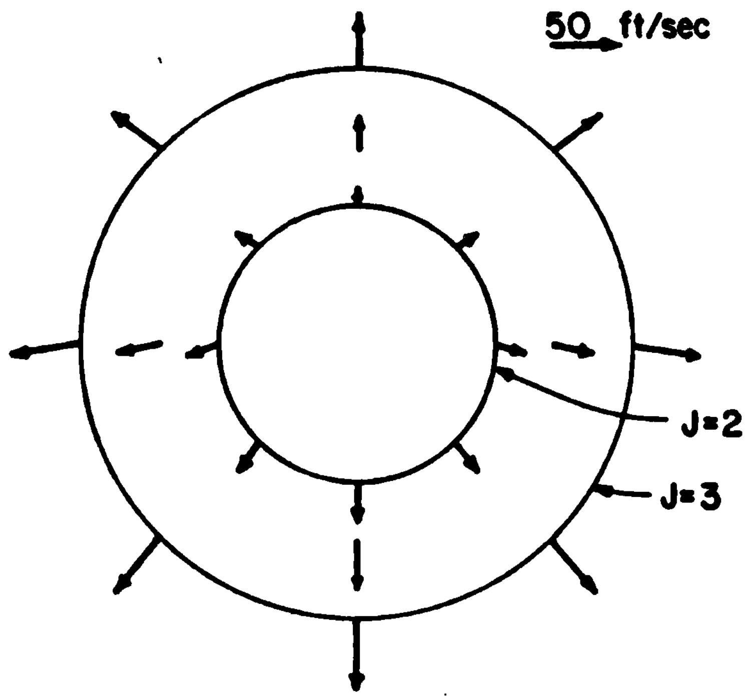
Flow Properties	
Stagnation Pressure, psia	4570
Stagnation Temperature, R	5987
Ratio of Specific Heats	1.15
Molecular Weight, products	26.71
Gas Constant, ft-lbf/(lbm-R)	57.85
Ambient Pressure, psia	14.7

Propellant Data	
Burn Rate at 2000 psi, in./sec	11.0
Pressure Exponent	0.7
Density, lbm/in^3	0.063



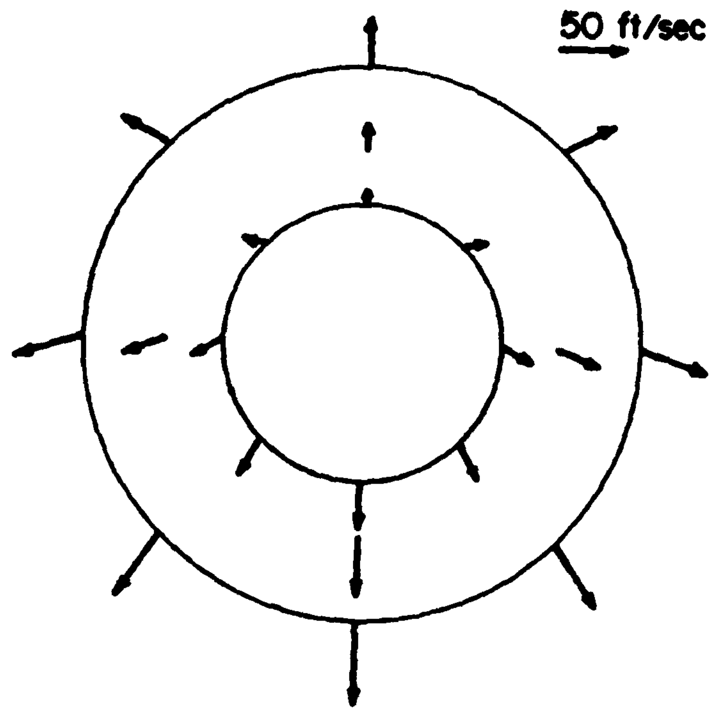
(a) $P-P_{90}$, psi.

Figure 16. Supersonic initial value surface.



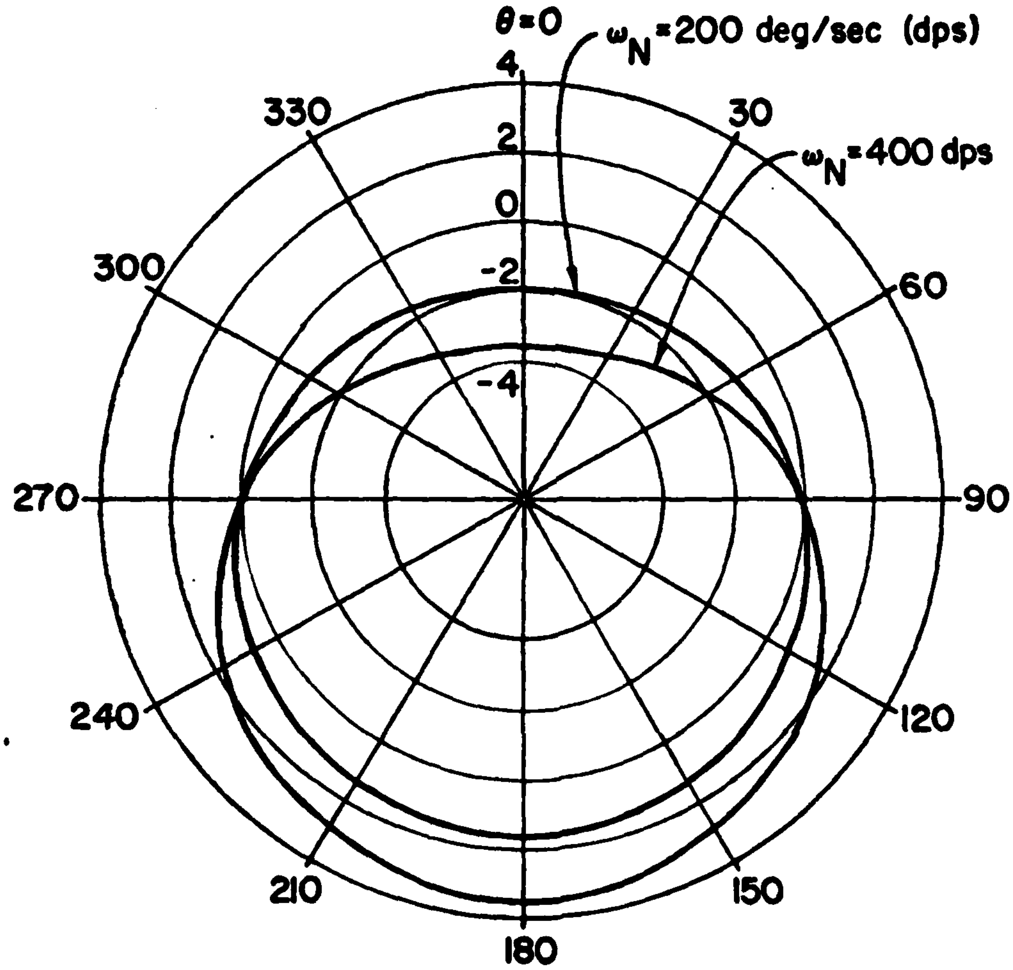
(b) Velocity field in the region of the centerline, $\omega_M = 400$ deg/sec.

Figure 16, continued.



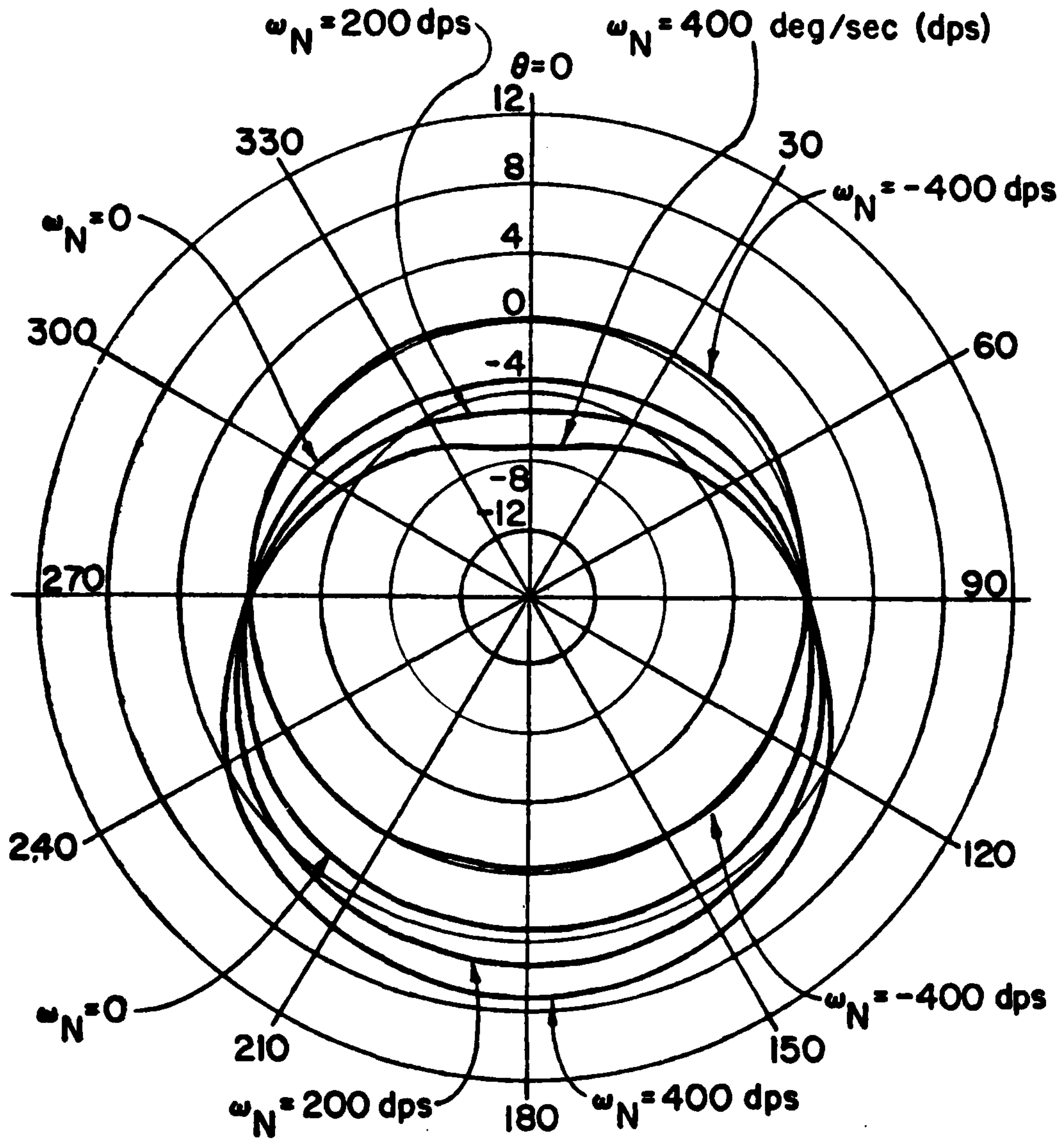
(c) Velocity field in the region of the centerline, $\omega_M = 800$ deg/sec.

Figure 16, continued.



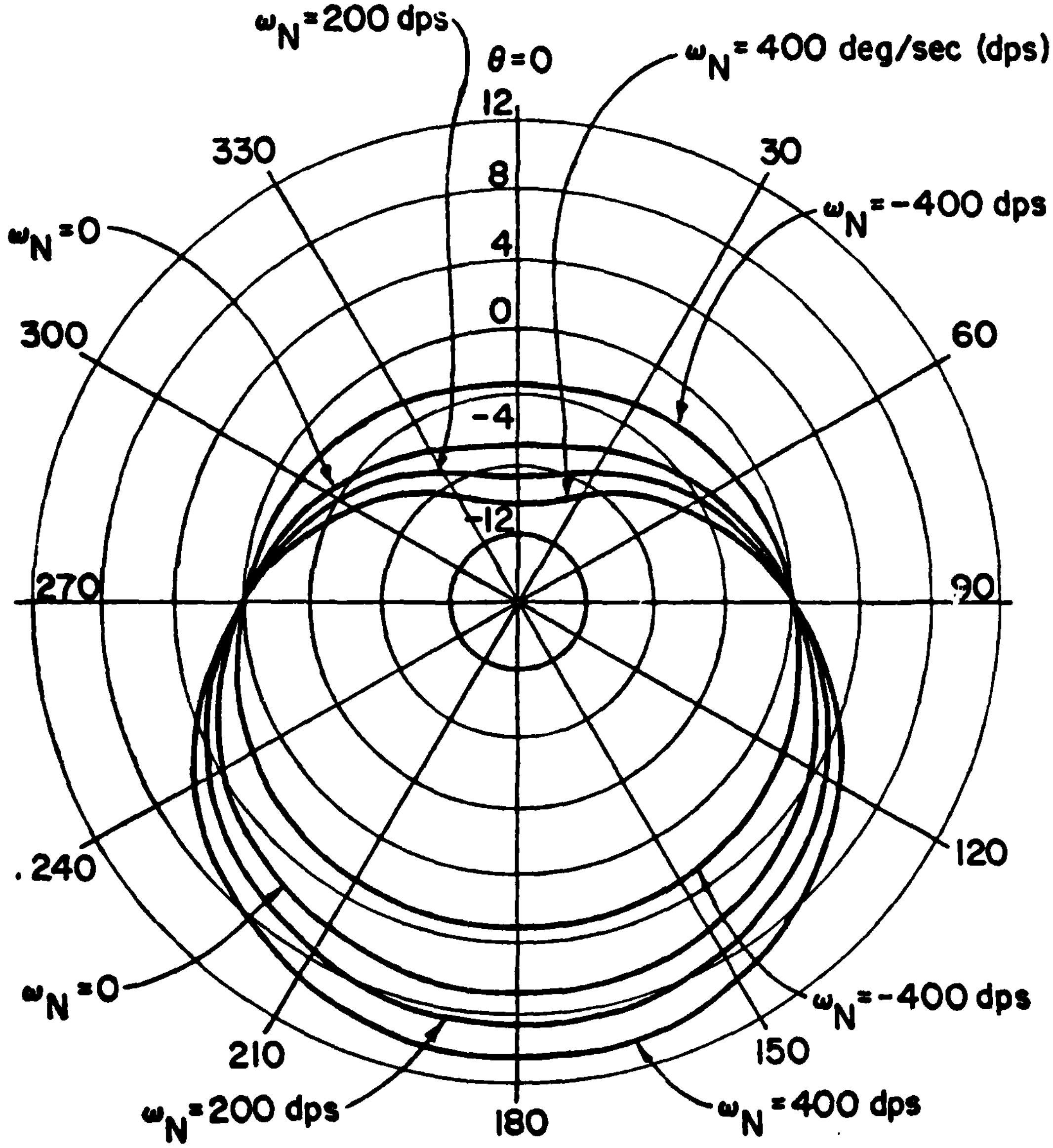
(a) Non-rotating missile.

Figure 17. Exit plane pressure distortion.



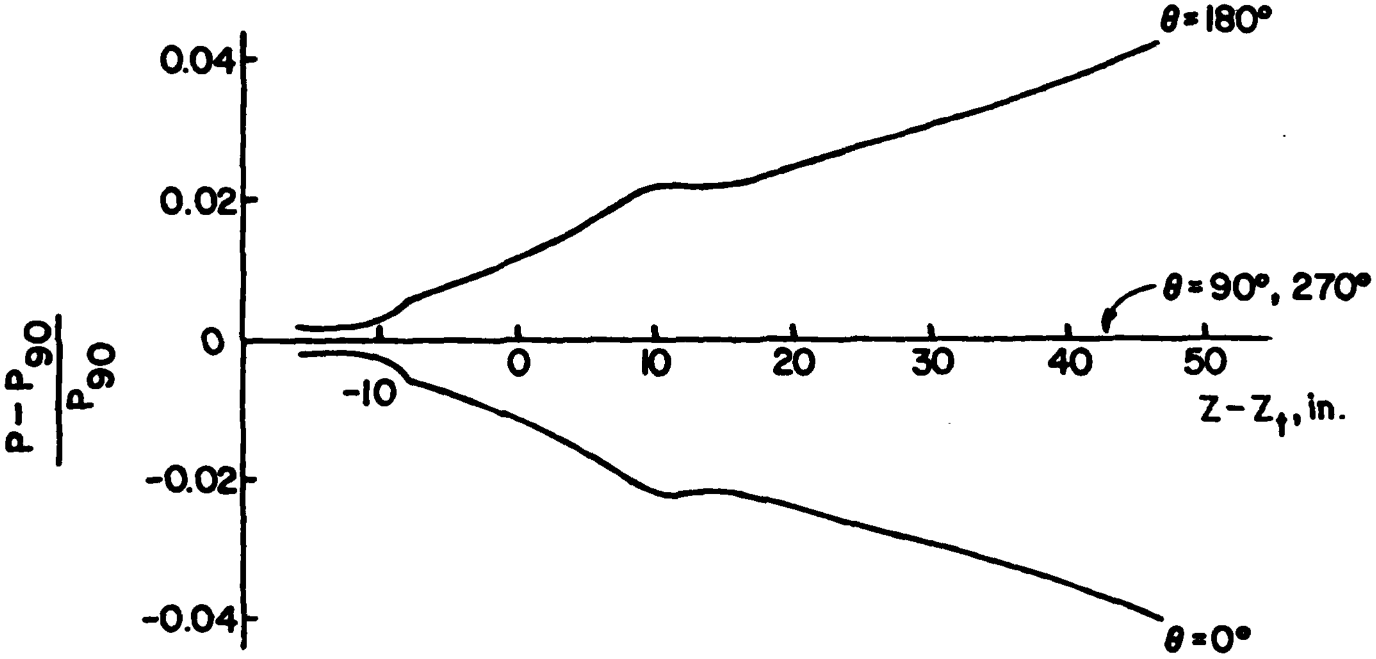
(b) Missile rotation, $\omega_M = 400$ deg/sec.

Figure 17, continued.



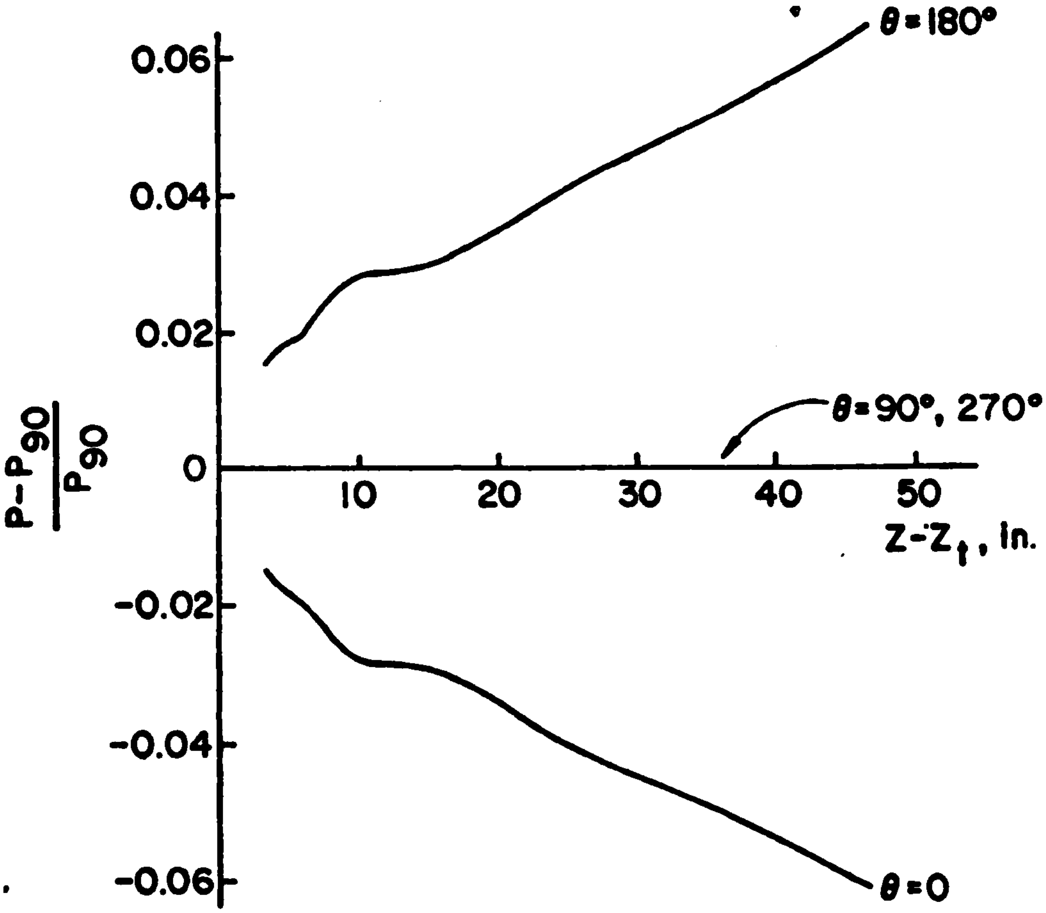
(c) Missile rotation, $\omega_M = 800$ deg/sec.

Figure 17, continued.



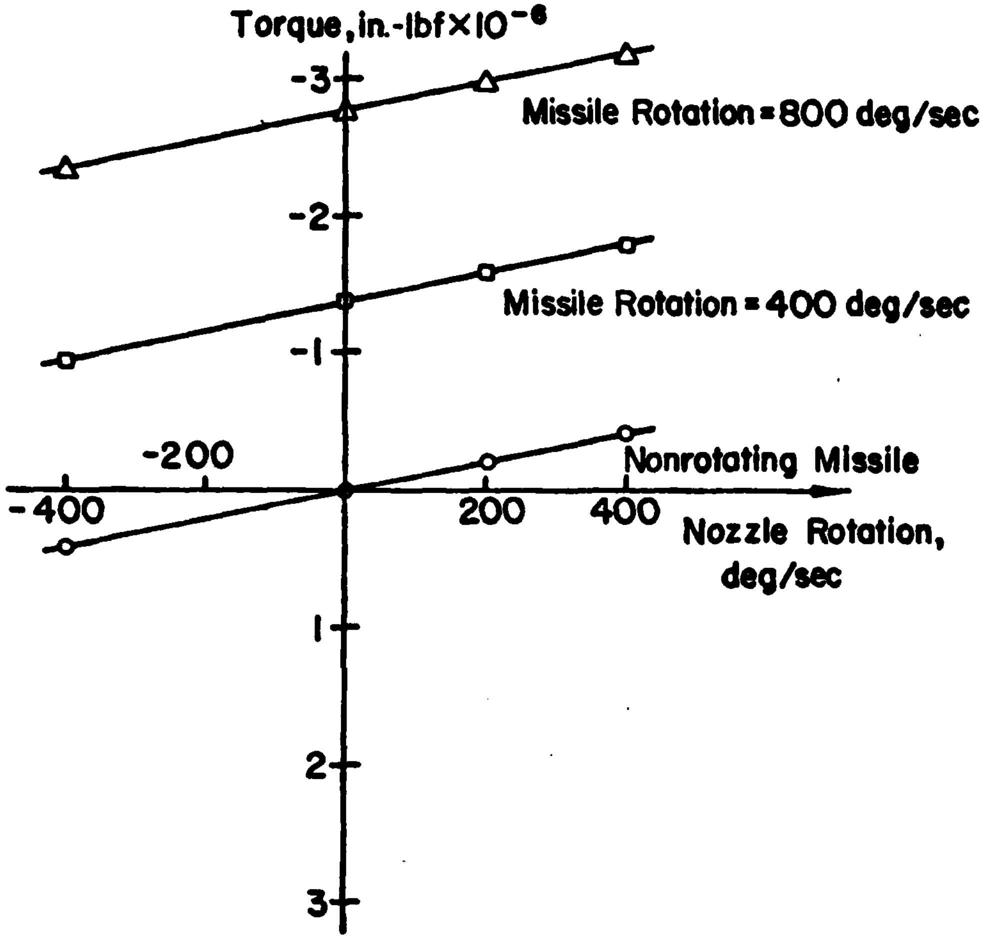
(b) Missile rotation, $\omega_M = 800$ deg/sec, nonrotating nozzle.

Figure 18, continued.



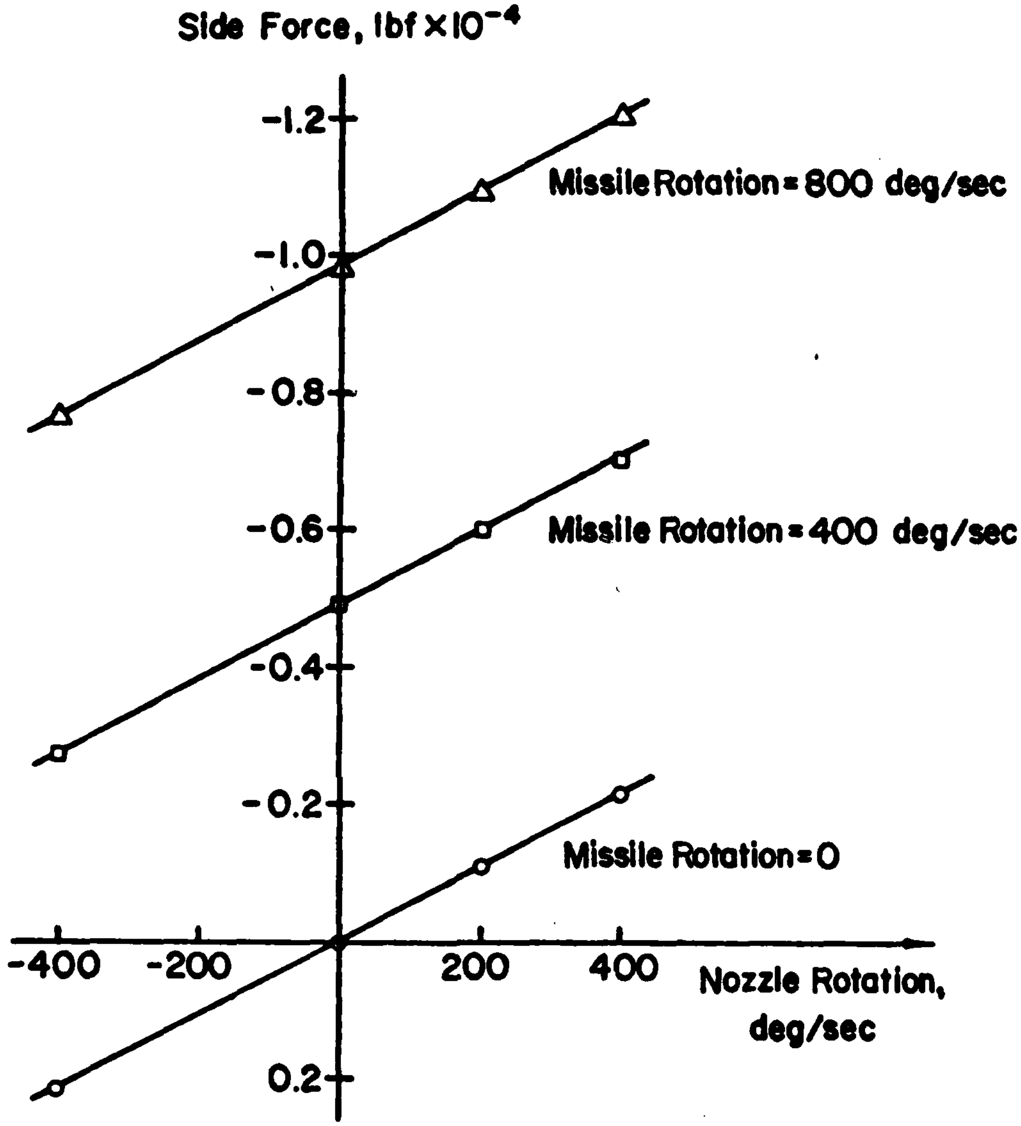
(c) ω_M=800 deg/sec, ω_N=400 deg/sec.

Figure 19, continued.



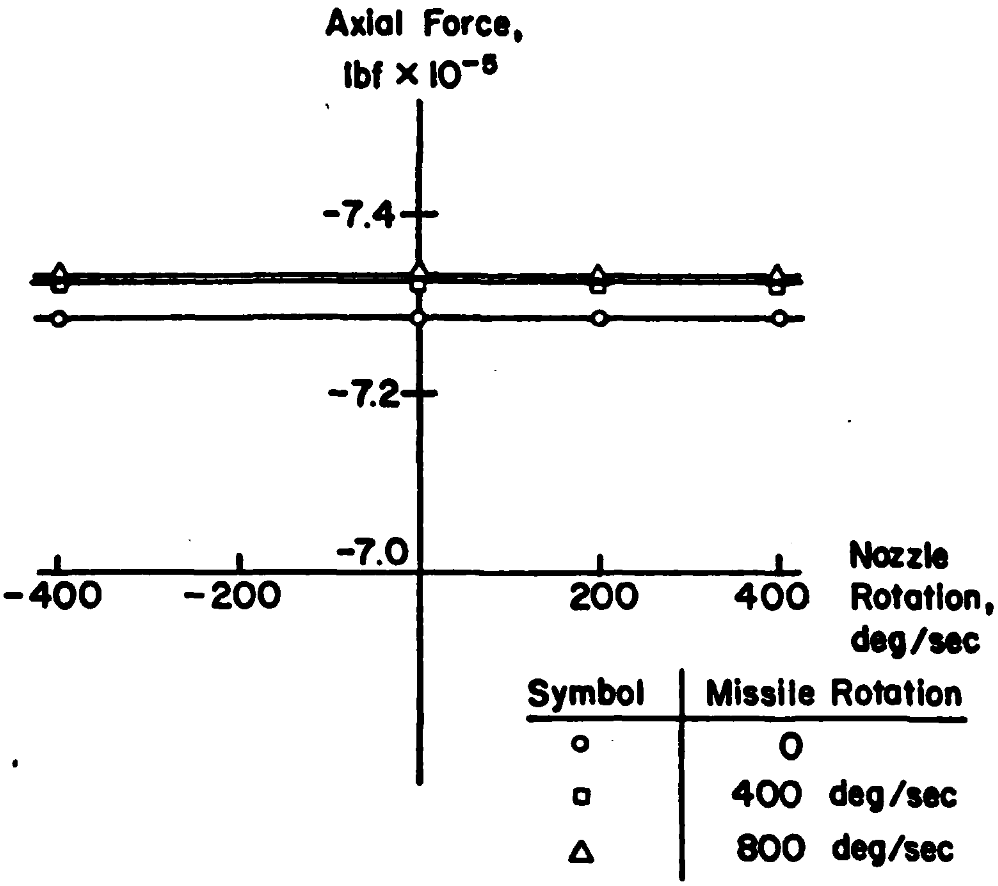
(a) Torque.

Figure 14. Effects of rotation on the forces and moments acting on the nozzle.



(b) Side force.

Figure 14, continued.



(c) Axial force.

Figure 14, continued.

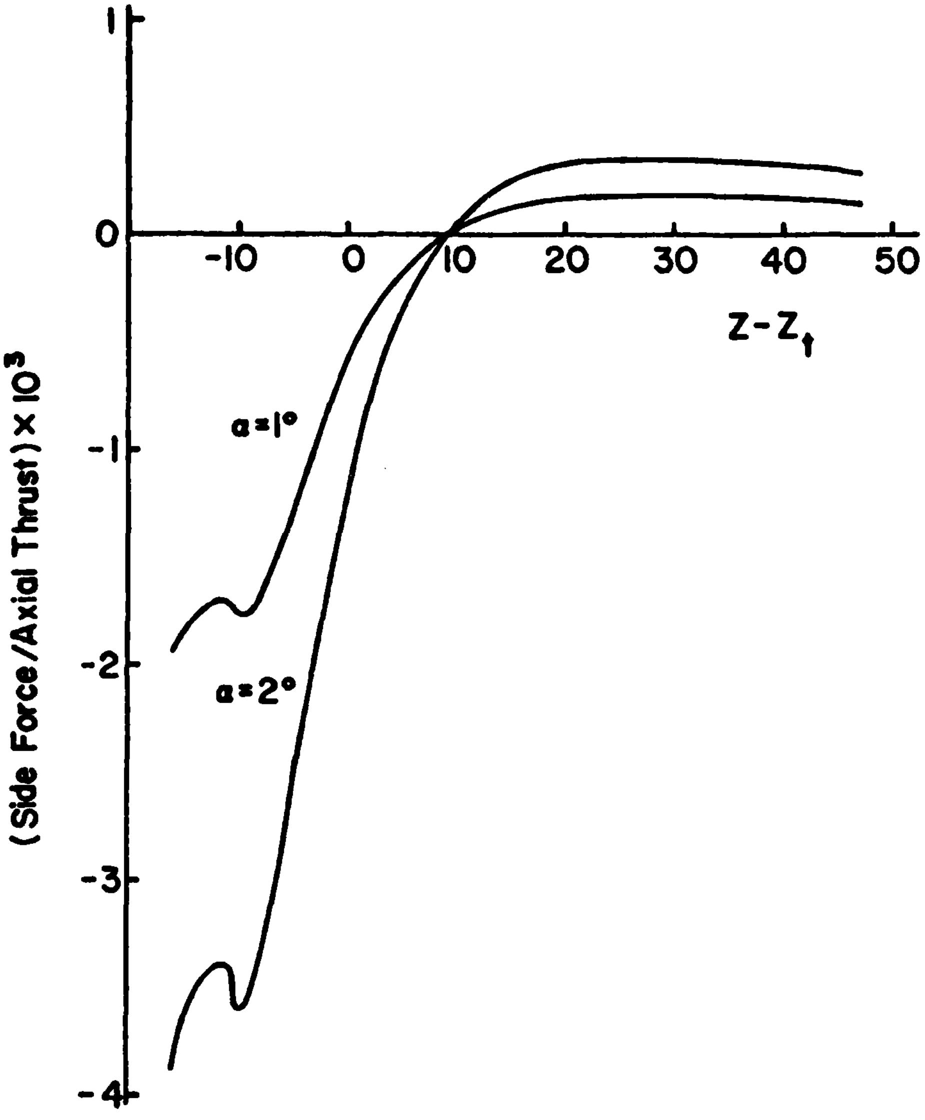


Figure 23. Side force to axial thrust ratio versus nozzle length.

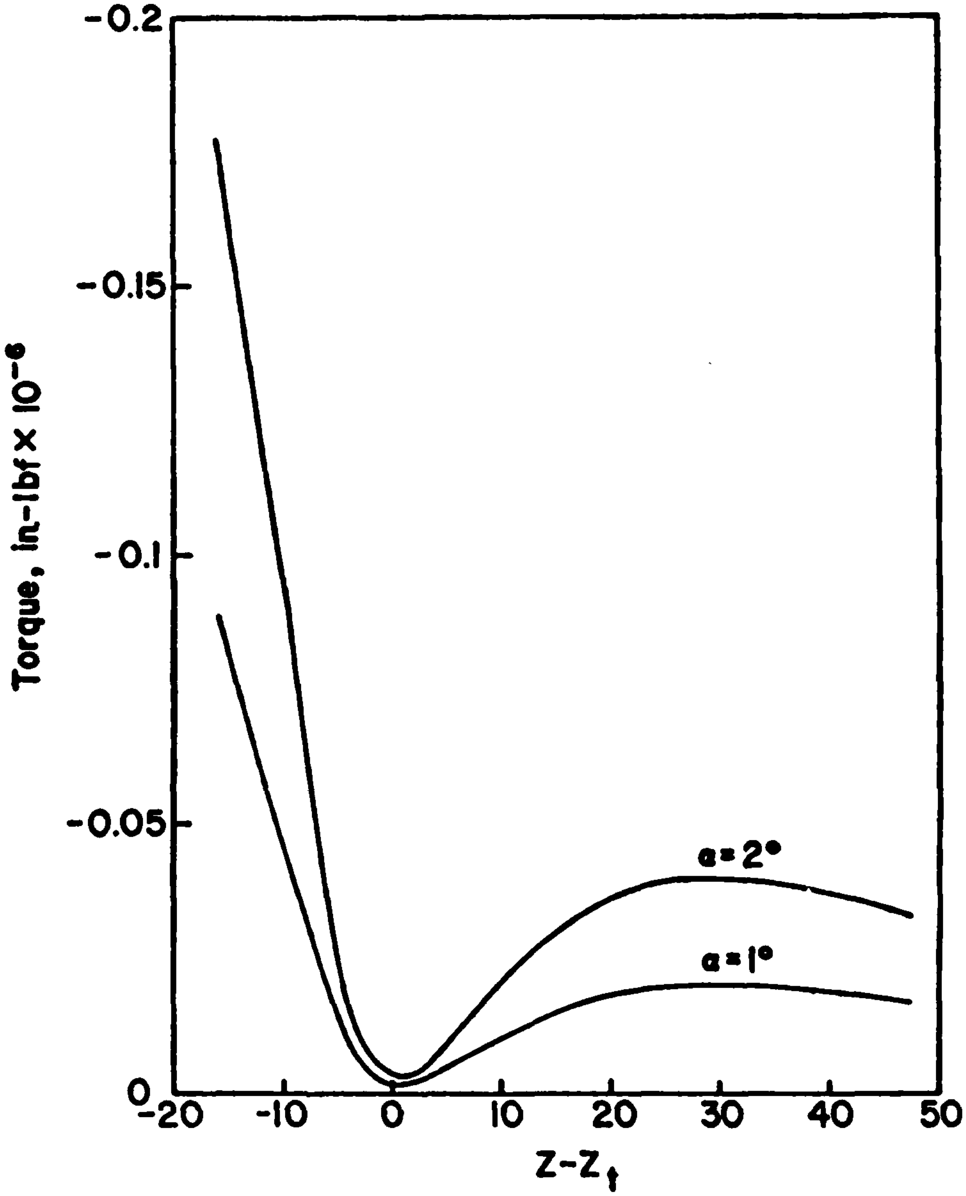


Figure 24. Misalignment torque versus nozzle length.

ADVANCED PERFORMANCE PREDICTION METHODOLOGY

JAY N. LEVINE

The goal of this discussion period will be to identify:

1. Limitations of present performance prediction methodologies

   a. SPP

   b. Technology in general

2. Impact of solid rocket motor technology developments on performance prediction methods.

The following items are listed to stimulate thinking about the subject. These items, as well as others suggested at the meeting, will be discussed. An effort will be made to catergorize the items into three groups.

1. Those items which are, or are very likely to be, important enought to definitely warrant that the ability to treat them be included in an advanced performance prediction methodology.

2. Those items which might be important, and should be carefully considered for inclusion in an advanced performance prediction methodology.

3. Those items which are not likely to be important, or have a significant effect on performance.

POSSIBLE ITEMS FOR DISCUSSION

1. Effect of all types of thrust vector control methods on performance
    a. Canted nozzles
    b. Gimbaled nozzles
    c. Jet interaction TVC
    d. Boundary layer TVC
2. Grain asymmetry, multidimensional ballistics
3. Non-circular cross-section nozzles
4. Scarfed nozzles
5. ENEC and very high area ratio nozzles
6. Spin effects
7. Nozzle wall roughness and asymmetrical nozzle erosion
8. Exotic propellant ingredients
9. Multi-propellant motors
10. Aerodynamic heating effects
11. Extreme motor operating conditions

In regards to the various loss mechanisms:

Two-phase
Divergence
Boundary layer
Kinetics
Submergence
Erosion
Combustion
Mass transfer between phases
Impingement

Which do you feel are modeled satisfactorily, at present? Which do you feel require additional work?

Joy Levine
AFRPL

OVERALL MOTOR EFFICIENCY CALC.

PRODUCT OF EFFICIENCIES

$$\eta_p = \Pi_i \, \eta_i$$

SUM OF EFFICIENCIES

$$\eta_s = 1 - \sum_{i=1}^{n} (1 - \eta_i)$$

LET: $\epsilon_i = 1 - \eta_i$

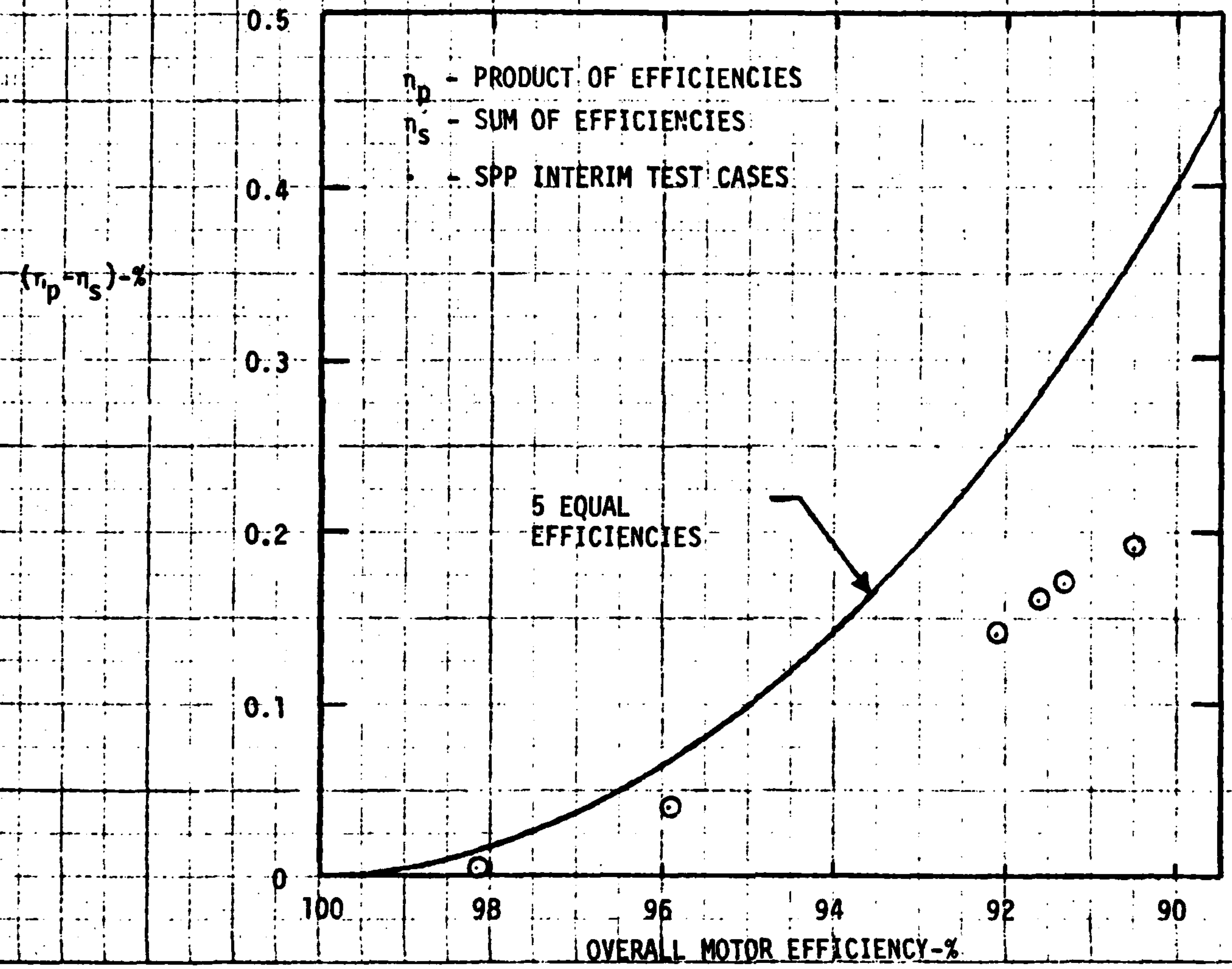
$$\eta_p = 1 - \sum_{i=1}^{n} \epsilon_i + \frac{1}{2} \sum_{\substack{i=1,n \\ j=1,n \\ i \neq j}} \epsilon_i \epsilon_j - O(\epsilon^3) + O(\epsilon^4)$$

$$\eta_p = \eta_s + \frac{1}{2} \sum_{\substack{i=1,n \\ j=1,n \\ i \neq j}} \epsilon_i \epsilon_j$$

$(\eta_p - \eta_s)$ is maximum when all of the η_i are equal

$$(\eta_p - \eta_s)_{max} = \frac{(n^2 - n)}{2} \epsilon^2$$

COMPARISON BETWEEN MAXIMUM AND ACTUAL DIFFERENCES BETWEEN OVERALL EFFICIENCY CALCULATIONS



ADVANCED PERFORMANCE PREDICTION METHODOLOGY

- LIMITATIONS OF PRESENT PERFORMANCE PREDICTION METHODOLOGIES
  - SPP
  - TECHNOLOGY IN GENERAL

- IMPACT OF SOLID ROCKET MOTOR TECHNOLOGY DEVELOPMENTS ON PERFORMANCE PREDICTION METHODS

- ASSESS AND PRIORITIZE TECHNOLOGY AREAS FOR INCLUSION IN ADVANCED PERFORMANCE PREDICTION METHODOLOGY
  - IMPORTANT - INCLUDE
  - MIGHT BE IMPORTANT - EVALUATE, INCLUDE IF WARRANTED
  - UNIMPORTANT - CAN BE EXCLUDED

POSSIBLE ITEMS FOR DISCUSSION

1. Effect of all types of thrust vector control methods on performance
   a. Canted nozzles
   b. Gimbaled nozzles
   c. Jet interaction TVC
   d. Boundary layer TVC
2. Grain asymmetry, multidimensional ballistics
3. Non-circular cross-section nozzles
4. Scarfed nozzles
5. ENEC and very high area ratio nozzles
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11. Extreme motor operating conditions

In regards to the various loss mechanisms:

- Two-phase
- Divergence
- Boundary layer
- Kinetics
- Submergence
- Erosion
- Combustion
- Mass transfer between phases
- Impingement

Which do you feel are modeled satisfactorily, at present? Which do you feel require additional work?

EXAMINATION OF RECENT MODELS FOR PARTICLE DRAG IN NOZZLE FLOWS

BY

MARK SALITA

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Thiokol/WASATCH DIVISION

INFORMATION ON THIS PAGE WAS PREPARED TO SUPPORT AN ORAL PRESENTATION AND CANNOT BE CONSIDERED COMPLETE WITHOUT THE ORAL DISCUSSION.

SUMMARY

- HERMSEN PRESENTED A "BEST" DRAG MODEL AT 12TH PSS MEETING BY CORRELATING ONLY UTC DRAG DATA (51 POINTS)
- SALITA HAS UTILIZED A LARGER DATA BASE CONSISTING OF ZARIN (46 POINTS AT HIGHER LAG REYNOLDS NUMBERS) AND BAILEY/HIATT (45 POINTS AT HIGHER LAG MACH NUMBERS) AS WELL AS THE UTC DATA
- THE DRAG COEFFICIENT WAS PREDICTED BY EACH OF 5 MODELS AND COMPARED TO THE MEASURED VALUES AT THOSE 142 R_e, M_p-POINTS
- CONCLUSIONS: HERMSEN MODEL IS BEST IN NOZZLES
  HENDERSON MODEL IS BEST IN PLUMES
- FURTHER DETAILS ARE PROVIDED IN THE FOLLOWING EXCERPT FROM THIOKOL MEMO NO. 2814-79-M105 (8/17/79)

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Results

The old familiar and more recent drag models have been compared to the data of UTC (Ref. 1), Zarin (Ref. 8) and Bailey/Hiatt (Ref. 9 for $Re_p \leq 40$). For each of the 51 UTC data points, 46 Zarin data points, and 45 Bailey/Hiatt data points the predicted C_D was normalized by the measured C_D. An average and root-mean-square (rms) error was then calculated for the j^{th} set of data from

$$E_{avg} = 1 - \frac{1}{n_j} \sum_{i=1}^{n_j} \left(\frac{C_{D_{predicted}}}{C_{D_{measured}}} \right)_i \tag{18}$$

$$E_{rms} = \sqrt{\frac{1}{n_j} \sum_{i=1}^{n_j} \left[1 - \left(\frac{C_{D_{predicted}}}{C_{D_{measured}}} \right)_i \right]^2} \tag{19}$$

A small rms error implies that the model correlates the data with very little scatter, while a small average error implies that the model predicts values near the middle of the scatter-band. The results are presented in Table III and the rms errors are summarized below:

	UTC		Zarin	Bailey/Hiatt	
	Nitrogen (35 points)	Freon (16 points)	All (46 points)	$M_p \leq 1.77$ (12 points)	$M_p > 1.77$ (32 points)
Kliegel (SPP)	2.17	1.65	0.09	0.09	0.24
Crowe (TPP)	0.14	0.16	0.21	0.27	0.15
Walsh	0.49	0.33	0.06	0.02	0.26
Henderson	0.15	0.20	0.09	0.05	0.05
Hermsen	0.11	0.11	0.06	0.10	0.30

The data is plotted together in Fig. 4.

Note that the Bailey/Hiatt data was arbitrarily divided into two groups by $M_p = 1.77$ (i.e. at the maximum M_p in the UTC data at which the Hermsen model was correlated). It is unlikely that $M_p > 1.77$ will ever be encountered in a rocket nozzle (although it might be in plumes) because

1) $M_p = \frac{\Delta V}{u_g} M_g$ shows that $M_p < 1.0$ everywhere in the subsonic region of the nozzle, even for the worst case of a stationary particle ($\Delta V = u_g$).

2) $M_p \sim \frac{d_p}{\sqrt{T_g}} < 0.7$ for a mean-size particle in a 53:1 nozzle (see Fig. 1).

The significance of the error in predicting the drag coefficients at high M_p is limited by the fact that there was a data scatter of nearly 20% in high-M_p low-Re_p test results.

Finally, all the above data was obtained in the absence of gas-stream turbulence. Some turbulence should exist in rocket motors, but Zarin has shown that the effect is probably negligible at the low-Re_p encountered there.

<u>Conclusions</u>

The above table shows that:

1) As expected the Kliegel model does well in the low-M_p slip/transition regime represented by the Zarin and Bailey/Hiatt data but fails badly as the free-molecular regime is encountered in the UTC data.
2) As expected the Crowe empirical relation does well for the free-molecular conditions of the UTC data it was forced to fit, but becomes less accurate for the slip/transition regime of the Zarin and Bailey/Hiatt data that it was not forced to fit.
3) As expected the Walsh correlation does well in fitting the Zarin and low-M_p Bailey/Hiatt data as it was forced to do, but fails to predict the free-molecular UTC data or the high-M_p Bailey/Hiatt data.
4) The Henderson model does quite well in predicting all the data at $\gamma_g = 1.40$, but not so well for freon ($\gamma_g = 1.09$).
5) The Hermsen model is the best predictive technique for $M_p \leq 1.77$ with small average and rms error for both free-molecular and slip-flow regimes; note that the Hermsen rms error in predicting the UTC data is no worse that the reported experimental accuracy (average of $\pm$ 11% for the 51 points - see Table I).
6) Thus the Hermsen model should be used for nozzle flows while the Henderson model may be better for plume flows where M_p might exceed 1.77 and γ_g is approaching 1.40.

Appendix 25: Problem - Measurement of Thrust for a Solid Rocket Fired in the Vertical Attitude

PROBLEM - MEASUREMENT OF THRUST FOR A

SOLID ROCKET FIRED IN THE VERTICAL ATTITUDE

PRESENTATION TO JANNAF PERFORMANCE

STANDARDIZATION SUBCOMMITTEE

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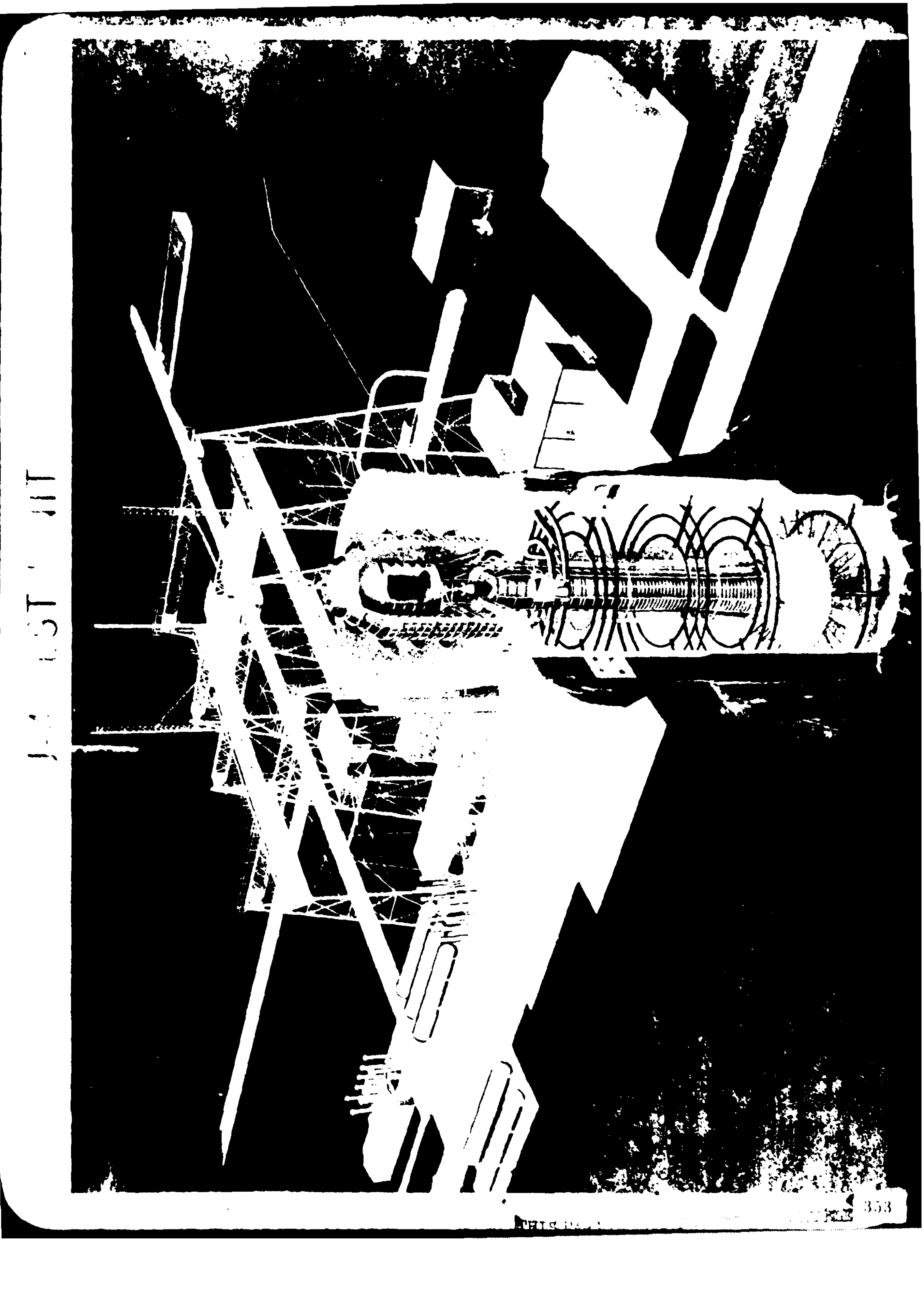
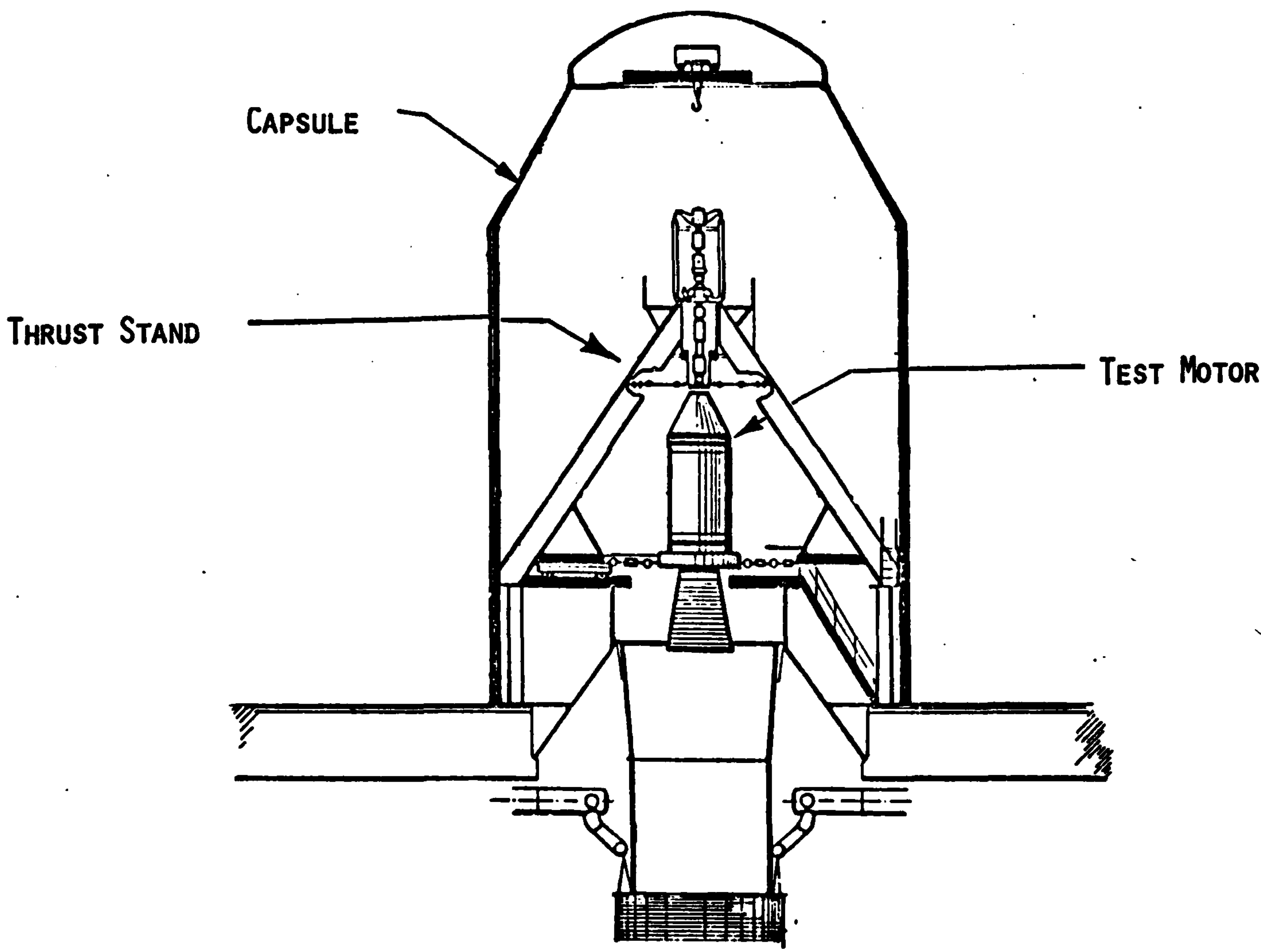
FEBRUARY 14-15, 1980

J-4 J-5 TEST COMPLEX



J-4 TEST CELL

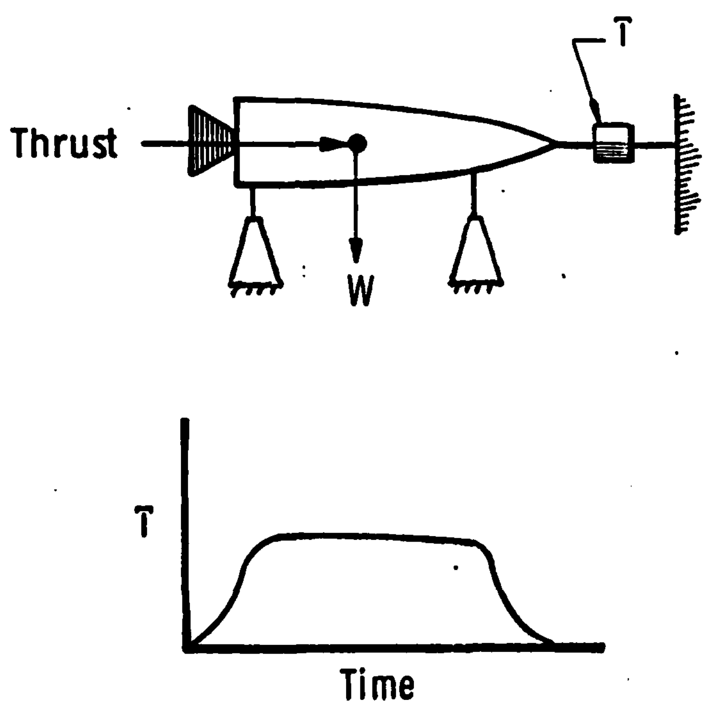


SOLID ROCKET MOTOR TESTING

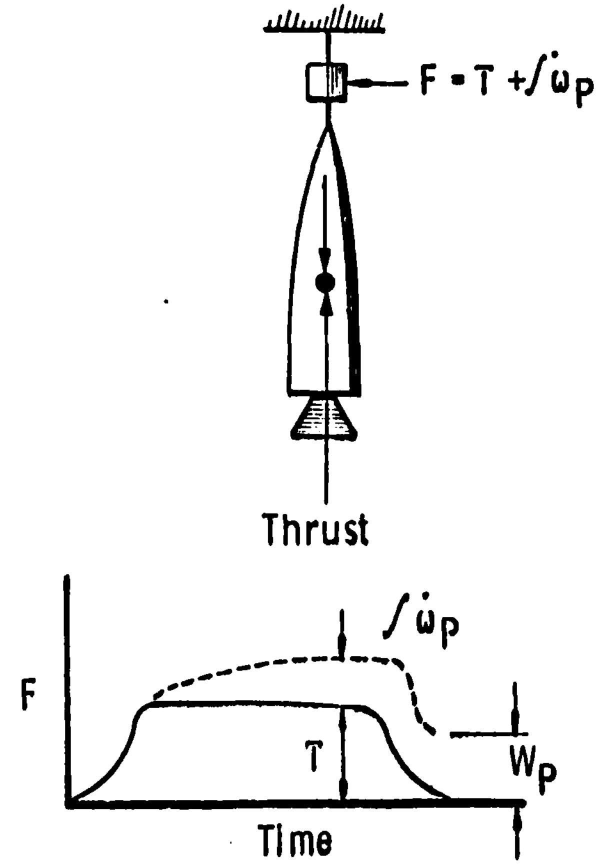
- TEST OBJECTIVES
  - TEST DURATION CAPABILITY
  - BURNING CHARACTERISTICS
  - COMPONENT DURABILITY
  - GIMBALING PROGRAM EVALUATION
  - TOTAL IMPULSE
  - VACUUM THRUST

VERTICAL THRUST MEASUREMENT

HORIZONTAL TESTING



VERTICAL TESTING



VACUUM THRUST - MEASURED VERTICALLY

- MEASURED FORCE, F_M
  - FUNCTION – MOTOR WEIGHT
  - FUNCTION – MOTOR THRUST
- ANALYTICAL EVALUATION
  - SEVERAL METHODS
  - DIFFERENT ASSUMPTIONS
  - QUALITY OF RESULTS

METHOD I

- ANALYTICAL EVALUATION* CONSTANT I_{SPV}
  - PARAMETER DEFINITION
    - F_M - VERTICAL FORCE MEASURED
    - P_A - TEST CELL PRESSURE MEASURED
    - W_I - INITIAL PREFIRE MOTOR WEIGHT
    - W_F - FINAL POSTFIRE MOTOR WEIGHT
    - A_E - EXHAUST NOZZLE EXIT AREA
    - ΔW - EXPENDED PROPELLANT = $W_I - W_F$

*FROM ANALYTICAL STUDY BY G. D. SMITH AND R. C. BAUER, SVERDRUP/ARO, INC., AEDC DIVISION

ASSUMPTIONS

- I_{SPV} = CONSTANT THROUGHOUT MOTOR BURN TIME = KNOWN
- ΔW = PROPELLENT EXPENDED

EQUATIONS

- 1) $I_{SPV} = F_V / \frac{DW}{DT}$

  FROM FORCE BALANCE

- 2) $F_M = F_V - W_T - P_A A_E$

  W_T = MOTOR WEIGHT AS FUNCTION TIME

- COMBINING EQ. (1) AND (2)
  - $F_M = I_{SPV} \frac{DW}{DT} - W_T - P_A A_E$

OR:

- 3) $\frac{DW}{DT} - \frac{W_T}{I_{SPV}} = \frac{F_M + P_A A_E}{I_{SPV}}$

SINCE:

  - I_{SPV} IS A GIVEN CONSTANT AND
  - F_M, P_A AND A_E ARE DIRECTLY MEASURABLE
- NUMERICALLY INTEGRATION OF EQ. 3
  - W_T AS A FUNCTION OF TIME

- WITH W_T KNOWN
  - EQ. 2 ($F_M = F_V - W_T - P_A A_E$)
  - WILL YIELD F_V AS A FUNCTION OF TIME
- EVALUATION OF ASSUMED VALUE OF I_{SPV}
  - NUMERICAL INTEGRATION OVER FIRING DURATION
  - $\int_0^t \left(\frac{DW}{DT}\right) DT = \Delta W = W_I - W_T$
  - ALLOWING REFINEMENT OF INITIAL ESTIMATE OF I_{SPV}

METHOD II

- PRESSURE, FLOW COEFFICIENTS

- ADDITIONAL PARAMETERS
- P_{CM} – CHAMBER PRESSURE (MEASURED AT HEAD OF MOTOR)
- K_C – CHAMBER PRESSURE CORRECTION FACTOR
- K_M – NOZZLE MASS FLOW COEFFICIENT
- A_I – INITIAL NOZZLE THROAT AREA
- A_F – FINAL NOZZLE THROAT AREA
- P_C – CHAMBER PRESSURE AT NOZZLE INLET

- ASSUMPTIONS
  - $P_C = K_C P_{CM}$
  - K_C, KNOWN AS A FUNCTION OF TIME
  - A^*, NOZZLE THROAT AREA, VARIATION CHARACTERISTICS KNOWN
  - K_M = A KNOWN CONSTANT
  - M^* = 1.0 CHOKED FLOW AT THROAT

EVALUATION

- FORCE BALANCE PREVIOUS EQ. 2
  - (2) $F_M = F_V - W - P_A A_E$
- ADDITIONALLY FOR $M^* = 1.0$:
  - (5) $\frac{DW}{DT} = K_M P_C A^*$

  AND:
  - $P_C = P_{CM} K_C$
- EQUATION (5) BECOMES
- EQ. (6) $\frac{DW}{DT} = -K_M K_C P_{CM} A^*$

- SINCE:
  - K_M & K_C - KNOWN PHYSICAL CONSTANTS
  - P_{CM} - MEASURED F(TIME)
- EQ. 6 INTEGRATED TO YIELD - MOTOR WEIGHT
  - W_T AS A FUNCTION OF TIME
- EQ. 2 WOULD YIELD F_V
- TOTAL IMPULSE I
  - $I = \int_0^t F_V(T)\,DT$

CALCULATION CHECKS

- WEIGHT CHANGE CALCULATED = WEIGHT CHANGE MEASURED
    - K_M - ADJUSTED
- A_T^* ASSUMED VARIATION COMPARE A_I & A_F MEASURED
    - A_T^* - ADJUSTED

EVALUATION OF METHODS I & II

- FV - UNCERTAINTY CALCULATION THROUGH ERROR PROPAGATION USING INFLUENCE COEFFICIENTS AND EQUATIONS OF METHODS I AND II

- INFLUENCE COEFFICIENTS

  INFLUENCE COEFFICIENTS SHOW THE EFFECT THAT A SMALL PERTURBATION OF AN INDEPENDENT VARIABLE HAS ON A DEPENDENT VARIABLE THROUGH AN EQUATION OF INTEREST AND FOR A SPECIFIC SET OF CONDITIONS.

- UNCERTAINTY - REF. CPIA NO. 180

  THE TERM "UNCERTAINTY" REPRESENTS THE MAXIMUM ERROR WE MIGHT REASONABLY EXPECT AND CONSISTS OF ESTIMATES OF BOTH BIAS AND PRECISION-TYPE ERRORS.

MAJOR SOURCES OF ERROR:

- INDEPENDENT PARAMETER — UNCERTAINTY

Independent Parameter	Uncertainty
F_M	$\pm$ 0.3%
I_{SPV}	$\pm$ 1.0%
P_{CM}	$\pm$ .5%
K_M	$\pm$ 1.0%
K_C	$\pm$ 0.1%

- RESULTING UNCERTAINTIES IN F_V
  - METHOD I = $\pm$ 0.4%
  - METHOD II = $\pm$ 0.8%

SUMMARY

- VACUUM THRUST CAN BE DETERMINED WHILE TESTING SOLID MOTORS IN A VERTICAL ATTITUDE WITH AN ACCEPTABLE DEGREE OF UNCERTAINTY.
- ADDITIONAL INFORMATION NEEDED:
  - ESTIMATES OF VALIDITY OF NECESSARY ASSUMPTIONS:
    - I_{SPV} = CONSTANT FOR SPECIFIC PROPELLANTS
    - MOTOR WEIGHT CHANGE = EXPENDED PROPELLANTS
  - INFORMATION ON VALUES OF K_C AND K_M
  - INFORMATION ON FORCE MEASUREMENTS MADE DURING VERTICAL ATTITUDE TESTING
- EVALUATIONS ON METHODS OTHER THAN I & II SHOWN HERE.

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