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Application of CFD Analyses to Design Support and Problem Resolution for ASRM and RSRM

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R. Harold Whitesides, ERC Incorporated

Abstract

The use of Navier-Stokes CFD codes to predict the internal flow field environment in a solid rocket motor is a very important analysis element during the design phase of a motor development program. These computational flow field solutions uncover a variety of potential problems associated with motor performance as well as suggesting solutions to these problems. CFD codes have also proven to be of great benefit in explaining problems associated with operational motors such as in the case of the pressure spike problem with the STS-54B flight motor. This paper presents results from analyses involving both motor design support and problem resolution. The issues discussed include the fluid dynamic/mechanical stress coupling at field joints relative to significant propellant deformations, the prediction of axial and radial pressure gradients in the motor associated with motor performance and propellant mechanical loading, the prediction of transition of the internal flow in the motor associated with erosive burning, the accumulation of slag at the field joints and in the submerged nozzle region, impingement of flow on the nozzle nose, and pressure gradients in the nozzle region of the motor.

The analyses presented in this paper have been performed using a two-dimensional axi-symmetric model. Fluent/BFC, a three dimensional Navier-Stokes flow field code, has been used to make the numerical calculations. This code utilizes a staggered grid formulation along with the SIMPLER numerical pressure-velocity coupling algorithm. Wall functions are used to represent the character of the viscous sub-layer flow, and an adjusted $\kappa-\varepsilon$ turbulence model especially configured for mass injection internal flows, is used to model the growth of turbulence in the motor port.

The topic of motor problem resolution is discussed by presenting solutions associated with the sixty-seven second burn time RSRM motor. The full motor internal flow environment for RSRM is discussed and the axial and radial pressure gradients are shown. The flow field environment and pressure gradients in the slots are also discussed. Particle traces from the burning propellant in the field joints are presented which show the tendency of the center and aft slots to collect slag. The flow field environment in the submerged nozzle region with and without slag in the submerged nozzle cavity is shown and specific flow field features which contribute to observed post-flight motor erosion patterns is discussed.

The design support analyses on the ASRM presented are for the zero second burn time geometry. The full motor flow field environment is presented along with axial and radial pressure gradients. Transition of the velocity profiles in the motor port is presented and the effect of the geometry flare in the bore at the aft end of the motor is shown. The aft slot deformation analysis is also presented. This analysis is an iterative coupled fluid dynamic/mechanical load analysis examining how two-dimensional flow field effects in the motor cause deformation of the propellant grain. The submerged nozzle region flow field is presented and discussed as it relates to the total pressure gradient observed in the aft end of the motor. The radial total pressure gradient is shown to be too great to allow the boot cavity motor pressure measurements to be compared with the nozzle end total pressure computed in ballistic runs.

Conclusions discussed in this paper consider flow field effects on the forward, center, and aft propellant grains except for the head end star grain region of the forward propellant segment. The field joints and the submerged nozzle are discussed as well. Conclusions relative to both the design evaluation of the ASRM and the RSRM scenarios explaining the pressure spikes were based on the flow field solutions presented in this paper.

APPLICATION OF CFD ANALYSES TO DESIGN SUPPORT AND PROBLEM RESOLUTION FOR ASRM AND RSRM

Richard A. Dill and R. Harold Whitesides

ERC, Inc.

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CFD METHODOLOGY

- GOVERNING EQUATIONS ARE THE 3-D ENSEMBLE-AVERAGED NAVIER STOKES EQUATIONS IN CONSERVATION FORM
- CLOSURE OF THE EQUATIONS BY THE STANDARD TWO-EQUATION $\kappa-\varepsilon$ MODEL OF TURBULENCE
- WALL FUNCTIONS USED TO DETERMINE NEAR WALL GRADIENTS
- DISCRETIZATION METHOD
    - GOVERNING EQUATIONS ARE WRITTEN IN COMPONENT FORM USING CONTRAVARIANT VELOCITY COMPONENTS
    - THIS ALLOWS THE USE OF A BOUNDARY FITTED CURVILINEAR COORDINATE SYSTEM
    - NUMERICAL METHOD IS FINITE VOLUME BASED
    - STAGGERED GRID STORAGE SYSTEM IS USED
    - CONVECTION AND DIFFUSION FLUXES ARE APPROXIMATED USING A POWER-LAW SCHEME
    - TIME DERIVATIVES ARE CALCULATED USING A FULLY IMPLICIT FIRST ORDER SCHEME
- PRESSURE-VELOCITY COUPLING IS ACCOMPLISHED BY USING THE SIMPLER ALGORITHM
- SOLVER USES LINEARIZED BLOCK IMPLICIT SCHEME

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RSRM ANALYSIS OBJECTIVES

- DEFINE INTERNAL MOTOR FLOW ENVIRONMENT TO SUPPORT INVESTIGATION OF RSRM PRESSURE SPIKES (STS-54B)
- PROVIDE PRESSURE LOADS ON CASTABLE AND NBR INHIBITORS TO DETERMINE DEFORMED SHAPE AND FAILURE MODES
- PROVIDE DETAILED FLOW FIELD DEFINITION IN SUBMERGED NOSE NOZZLE REGION TO SUPPORT EVALUATION OF SLAG PHENOMENA
- DETERMINE RELATIVE PROPENSITY OF THE FORWARD, CENTER, AND AFT SLOTS FOR COLLECTING SLAG USING PARTICLE TRAJECTORY ANALYSIS

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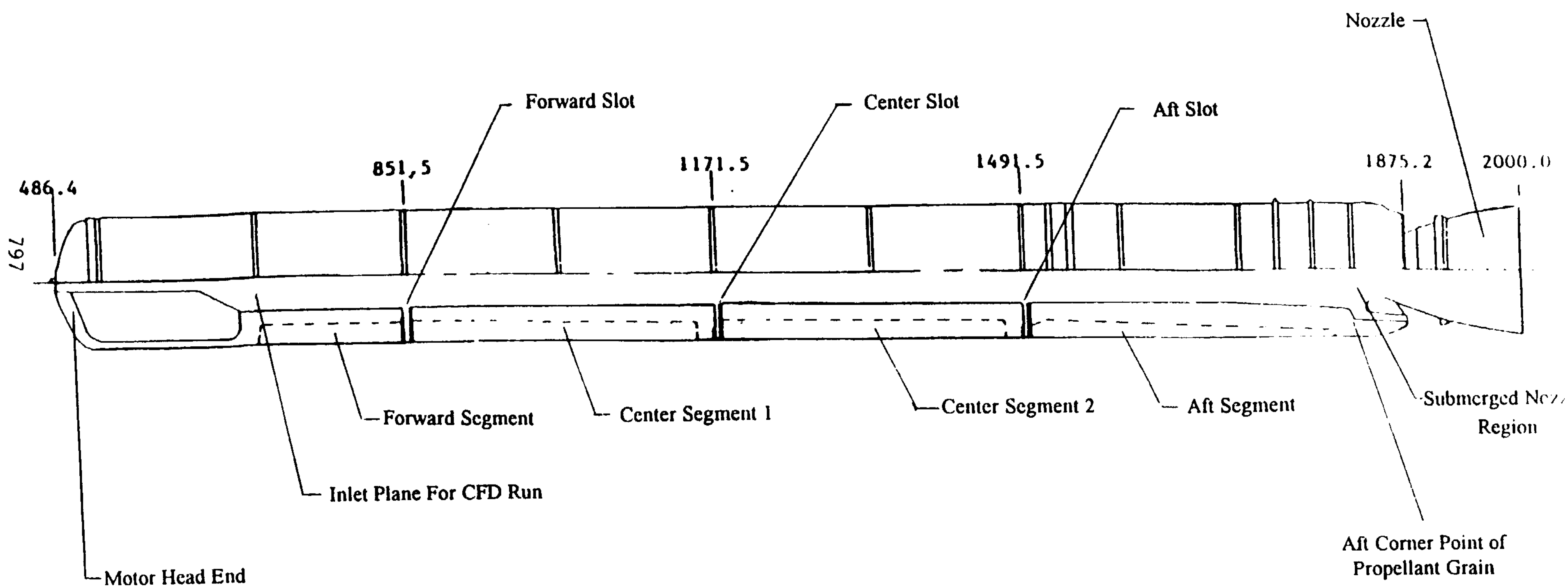
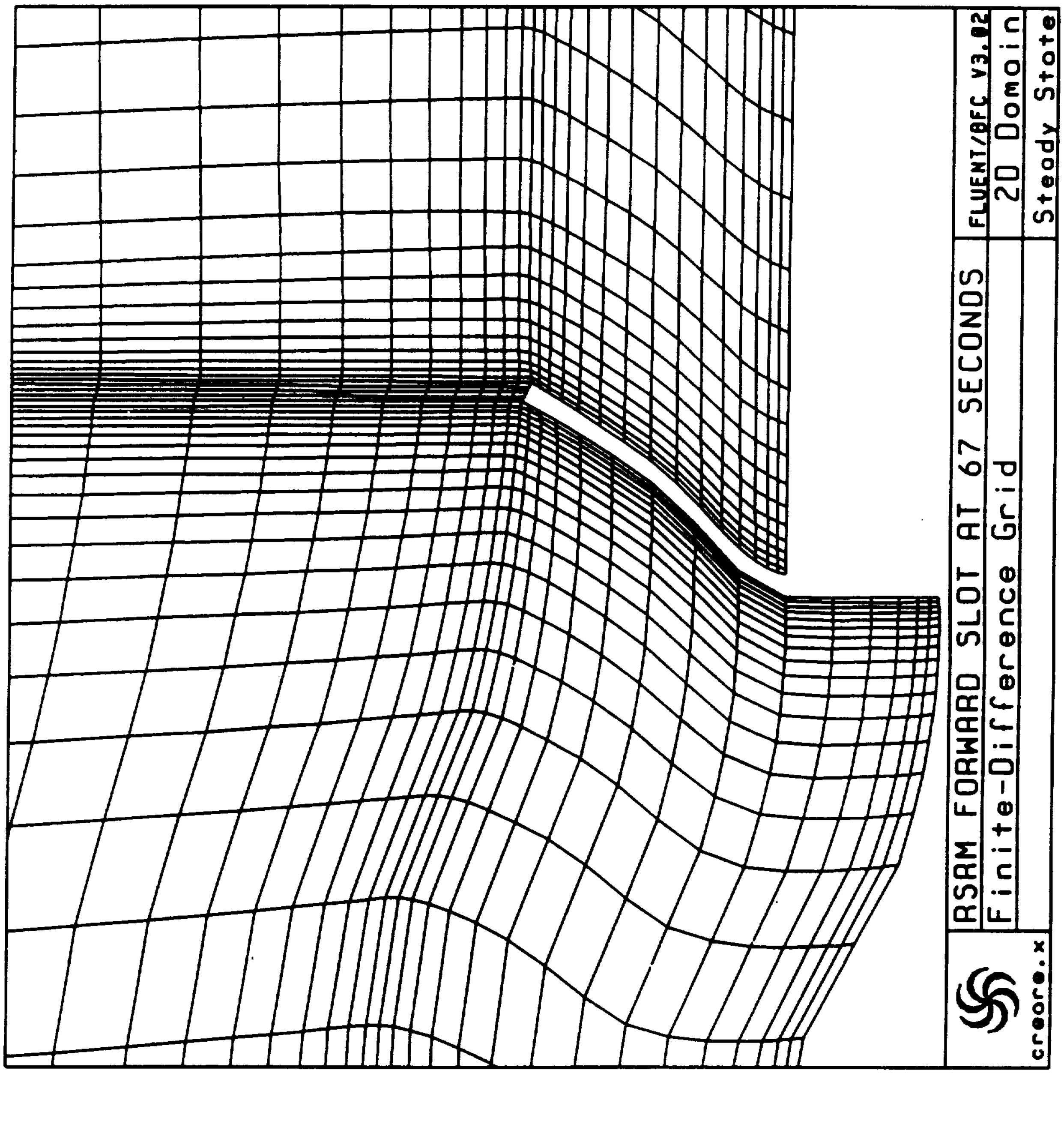
RSRM Motor Geometry



(Dashed Line Shows The 67 Second Burn Back)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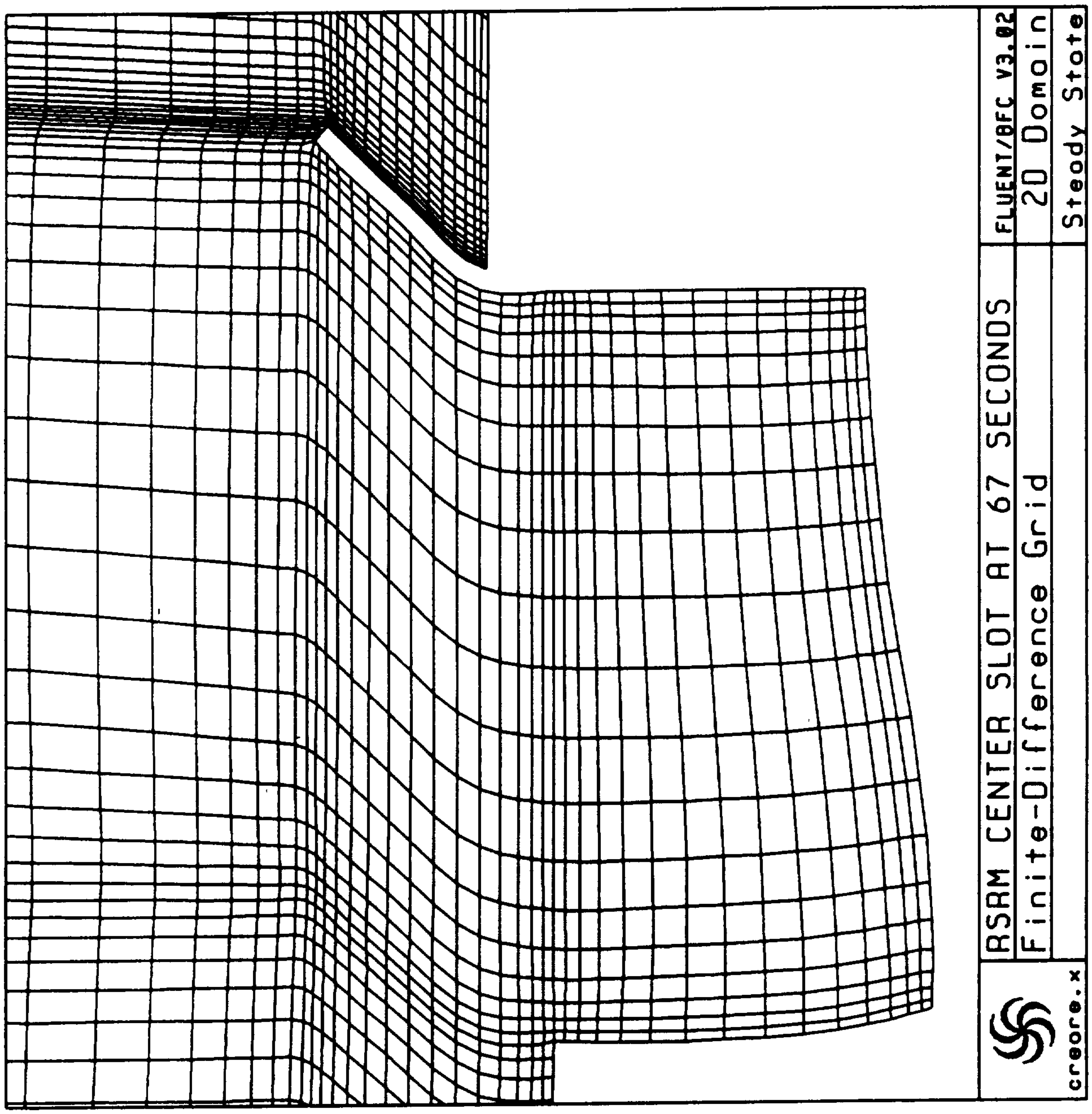
FLUENT/BFC V3.02
2D Domain
Steady State
creare.x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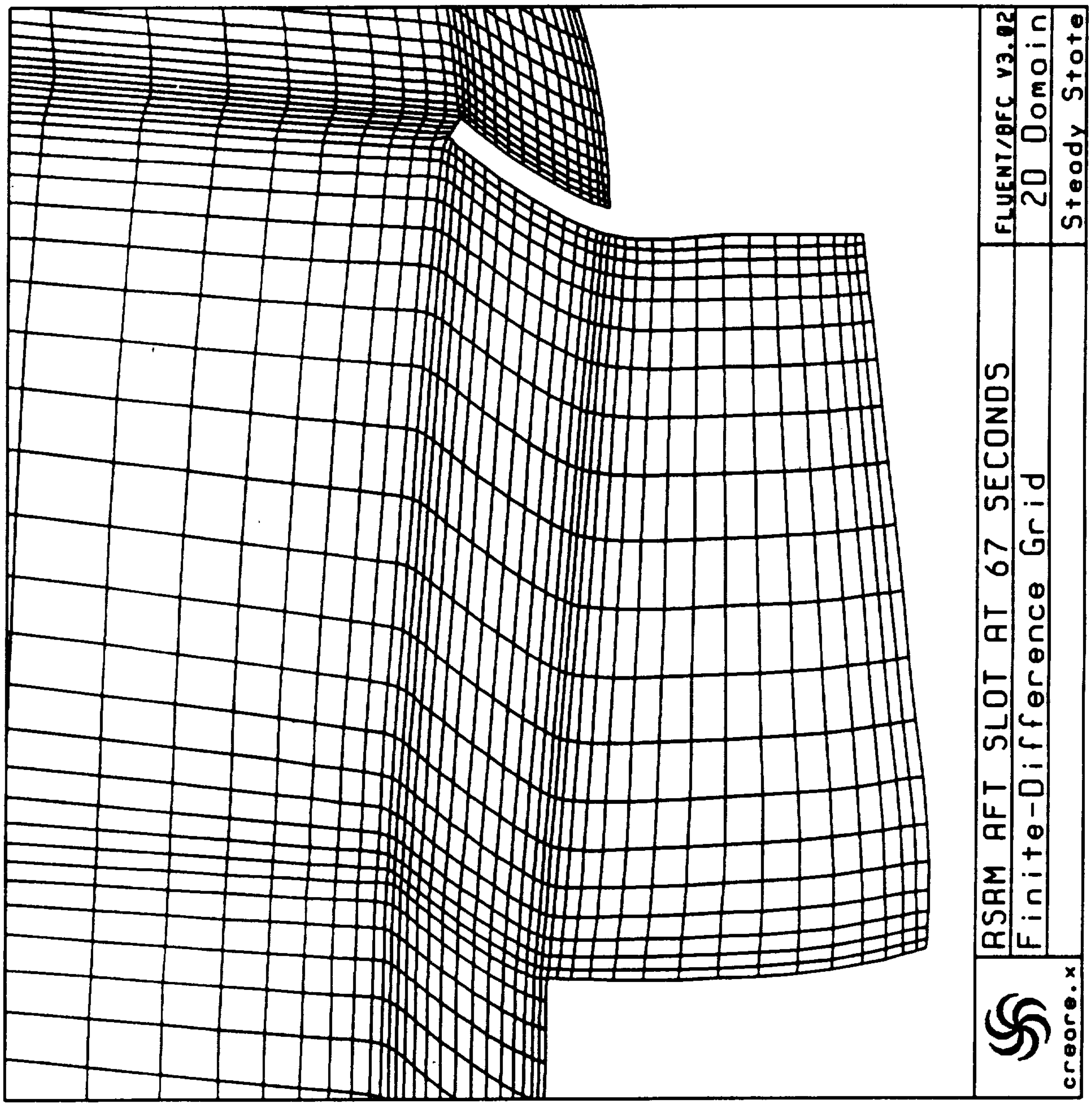
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2D Domain
Steady State
creare.x

RSRM MOTOR BOUNDARY CONDITIONS

67 SECOND MOTOR BURN TIME CONFIGURATION

MOTOR AFT SEGMENT END OF GRAIN PRESSURE	625.2 psia
HEAD END PORT VELOCITY	12.47 ft/sec
TOTAL TEMPERATURE	6093°K
$\dot{M}$ (FORWARD SEGMENT)	1555.9 lbm/sec
$\dot{M}$ (CENTER SEGMENT 1)	2587.5 lbm/sec
$\dot{M}$ (CENTER SEGMENT 2)	2578.6 lbm/sec
$\dot{M}$ (AFT SEGMENT)	2849 lbm/sec
MOLECULAR WEIGHT OF EQUIVALENT GAS	28.04
DYNAMIC VISCOSITY	6.189×10^{-5} lbm/ft-sec
SPECIFIC HEAT RATIO	1.138

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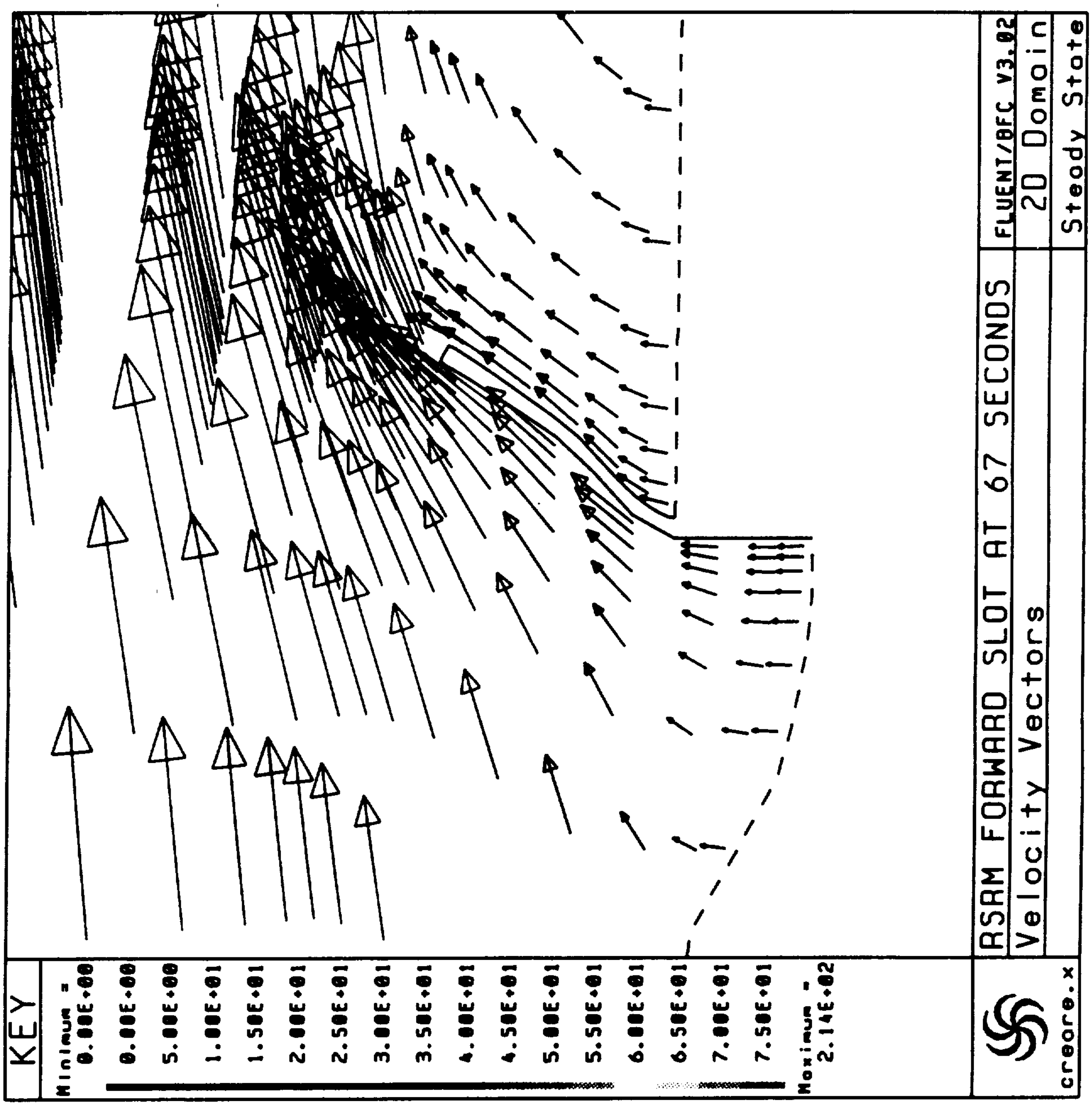
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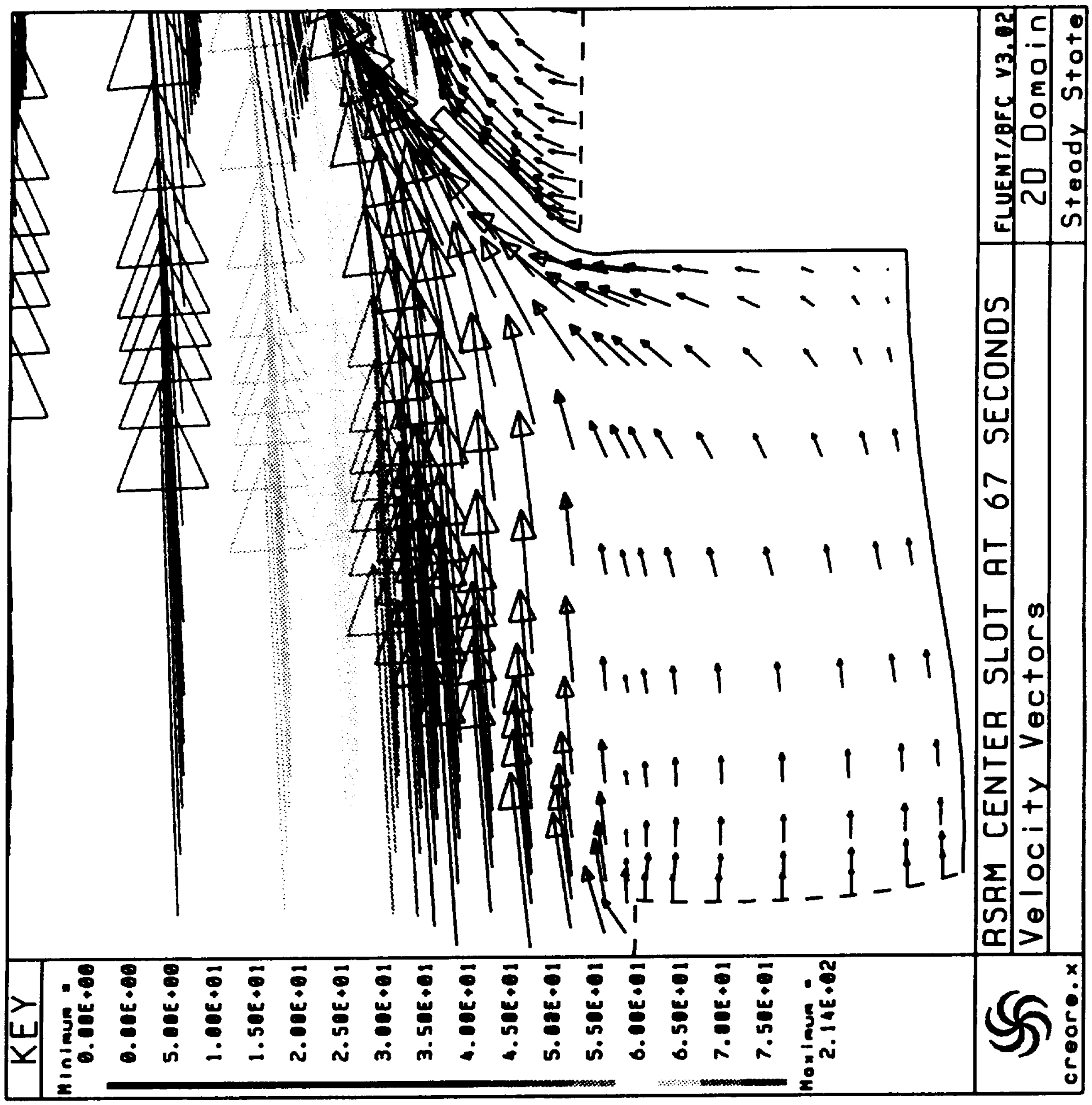
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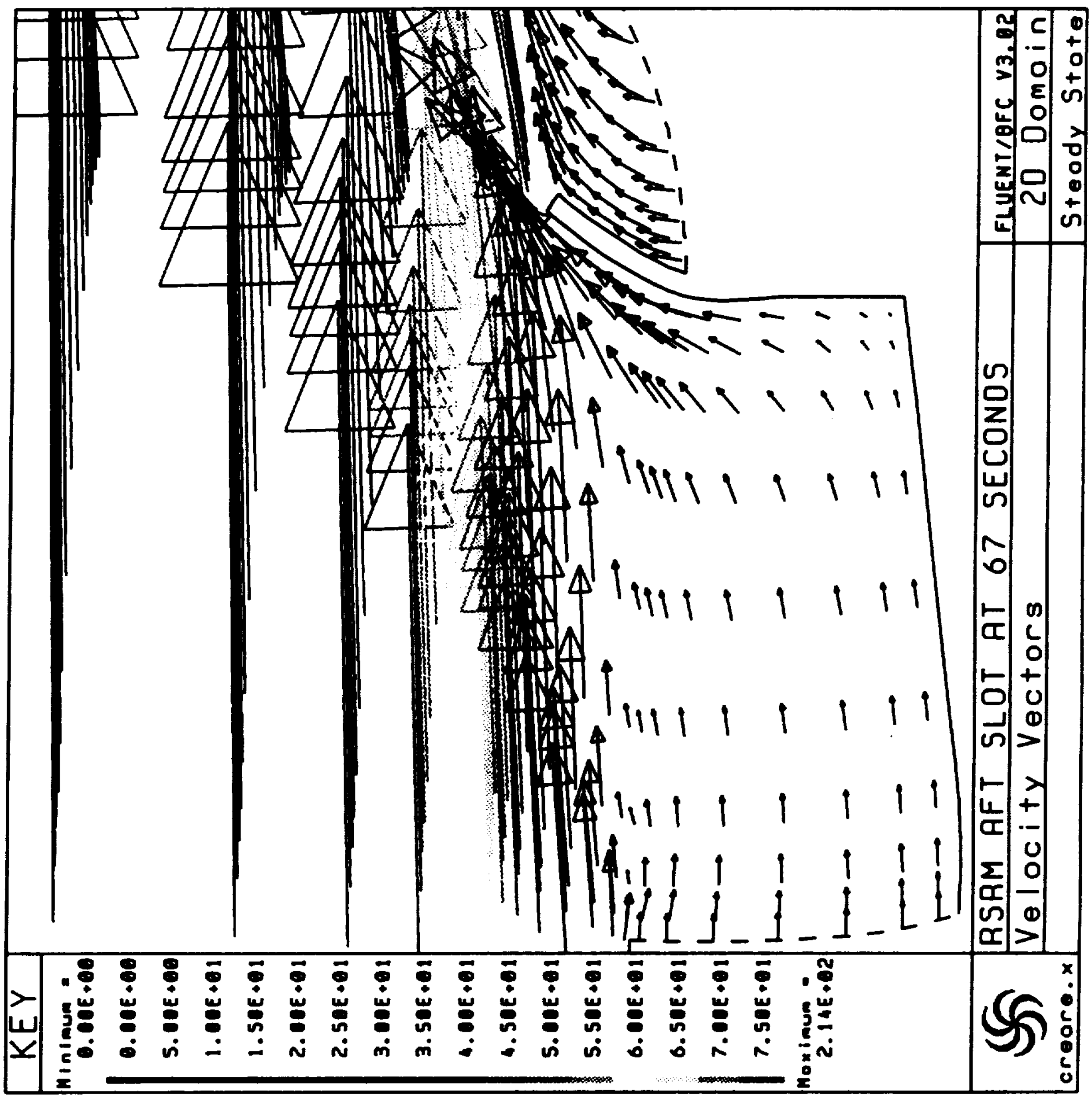

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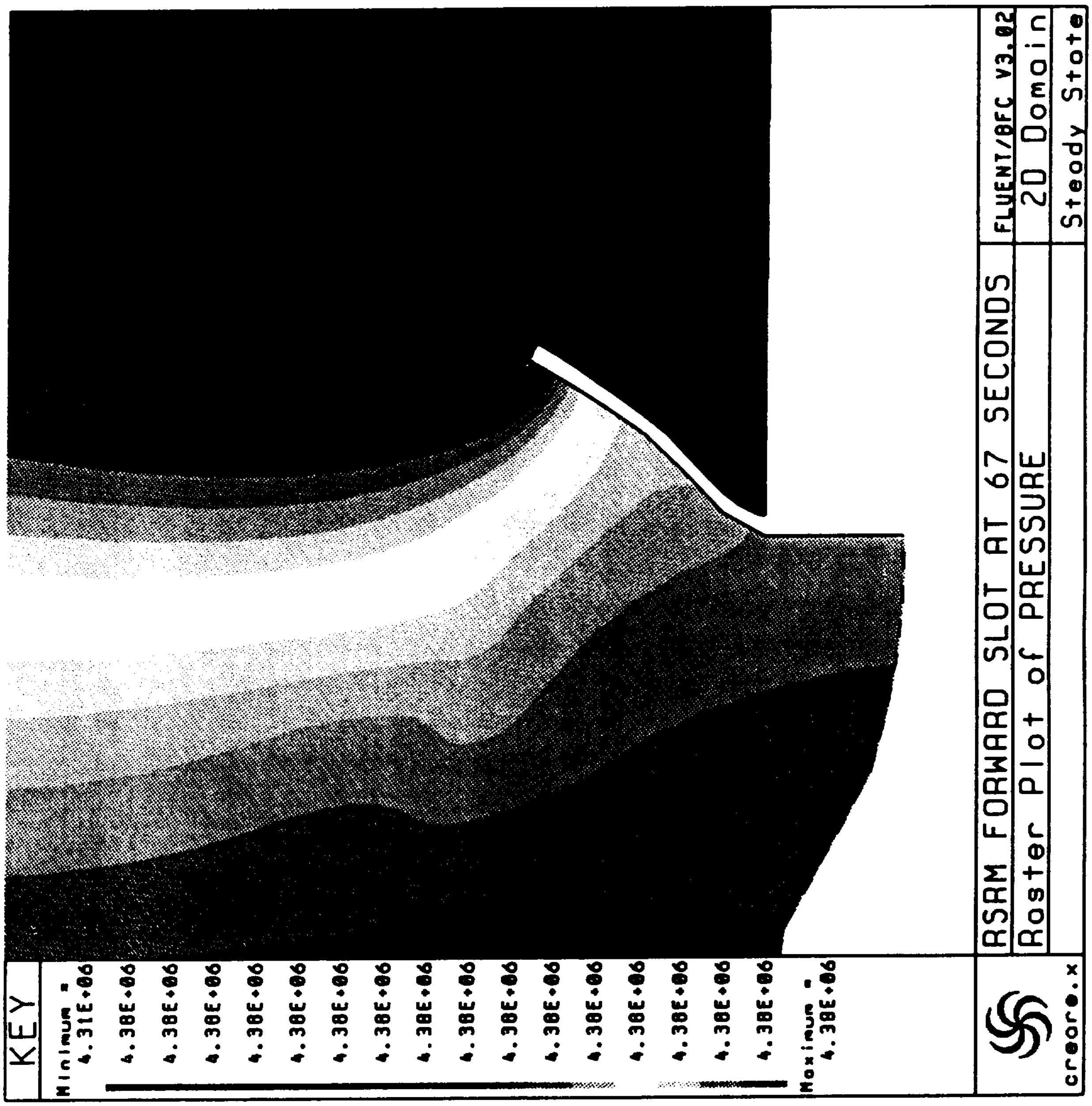
FLUENT/BFC V3.02
2D Domain
Steady State



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Raster Plot of PRESSURE
FLUENT/BFC V3.02
2D Domain
Steady State
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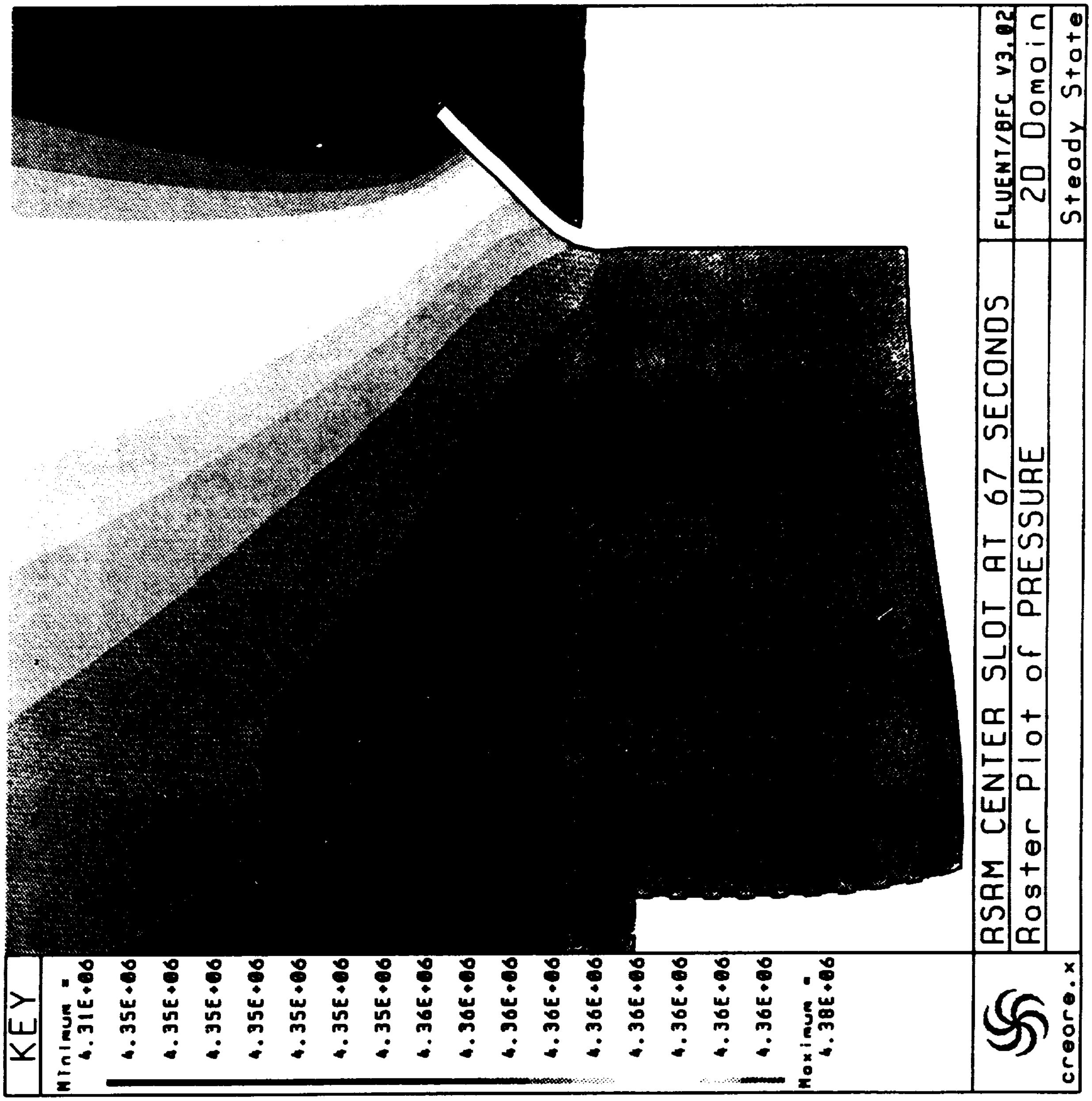

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2D Domain
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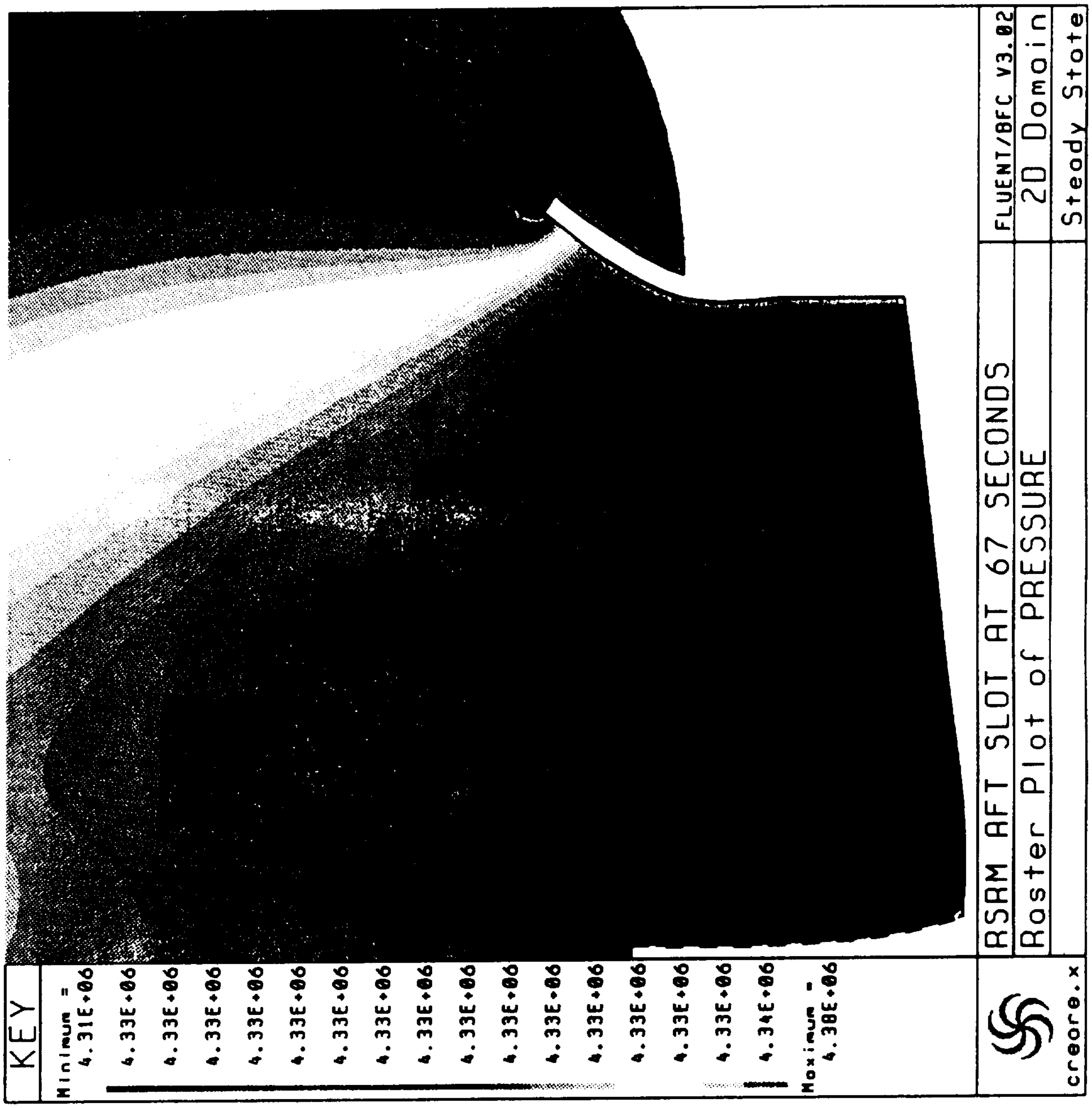

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2D Domain
Steady State
creare.x
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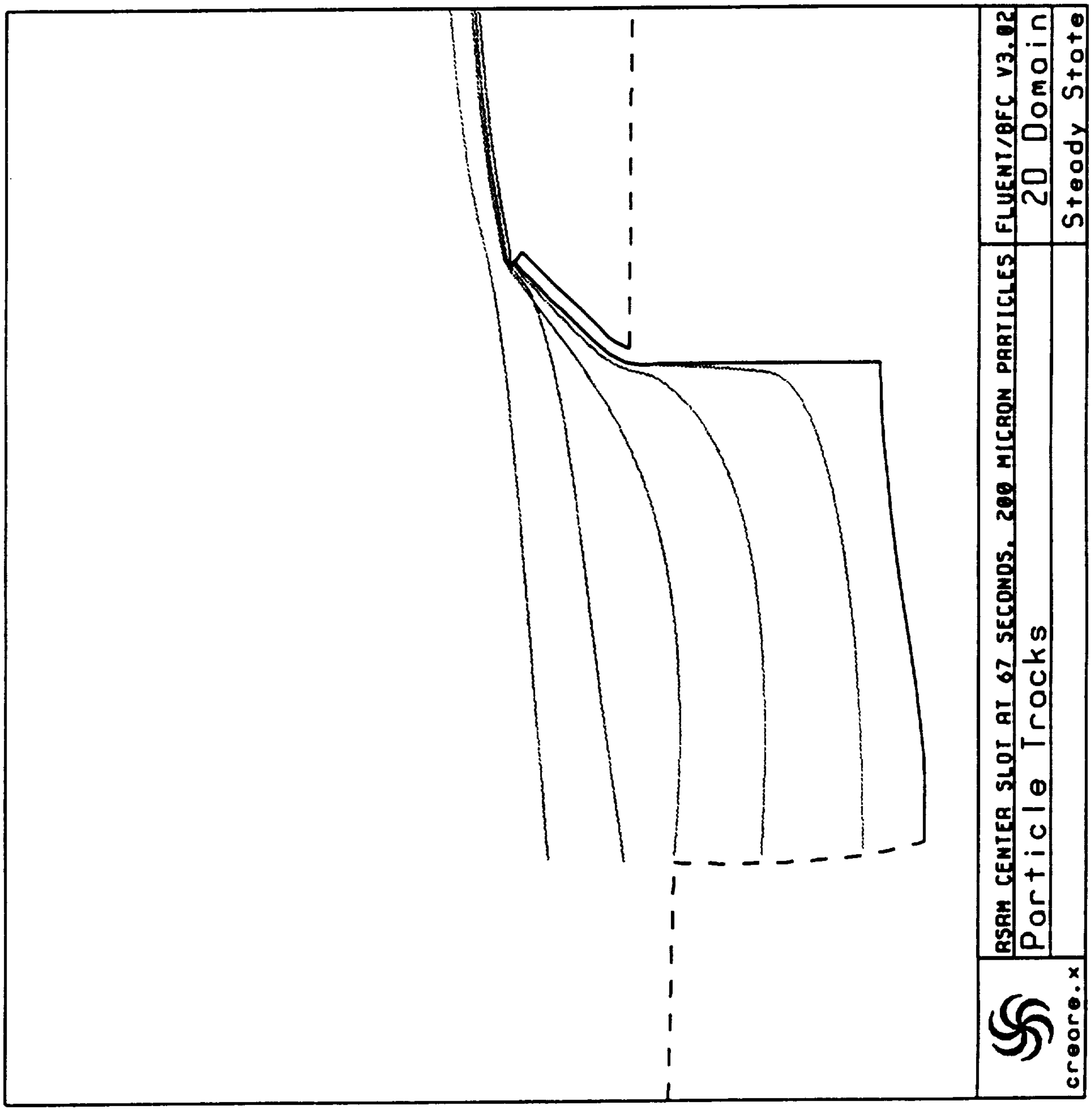
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Particle Tracks
2D Domain
Steady State
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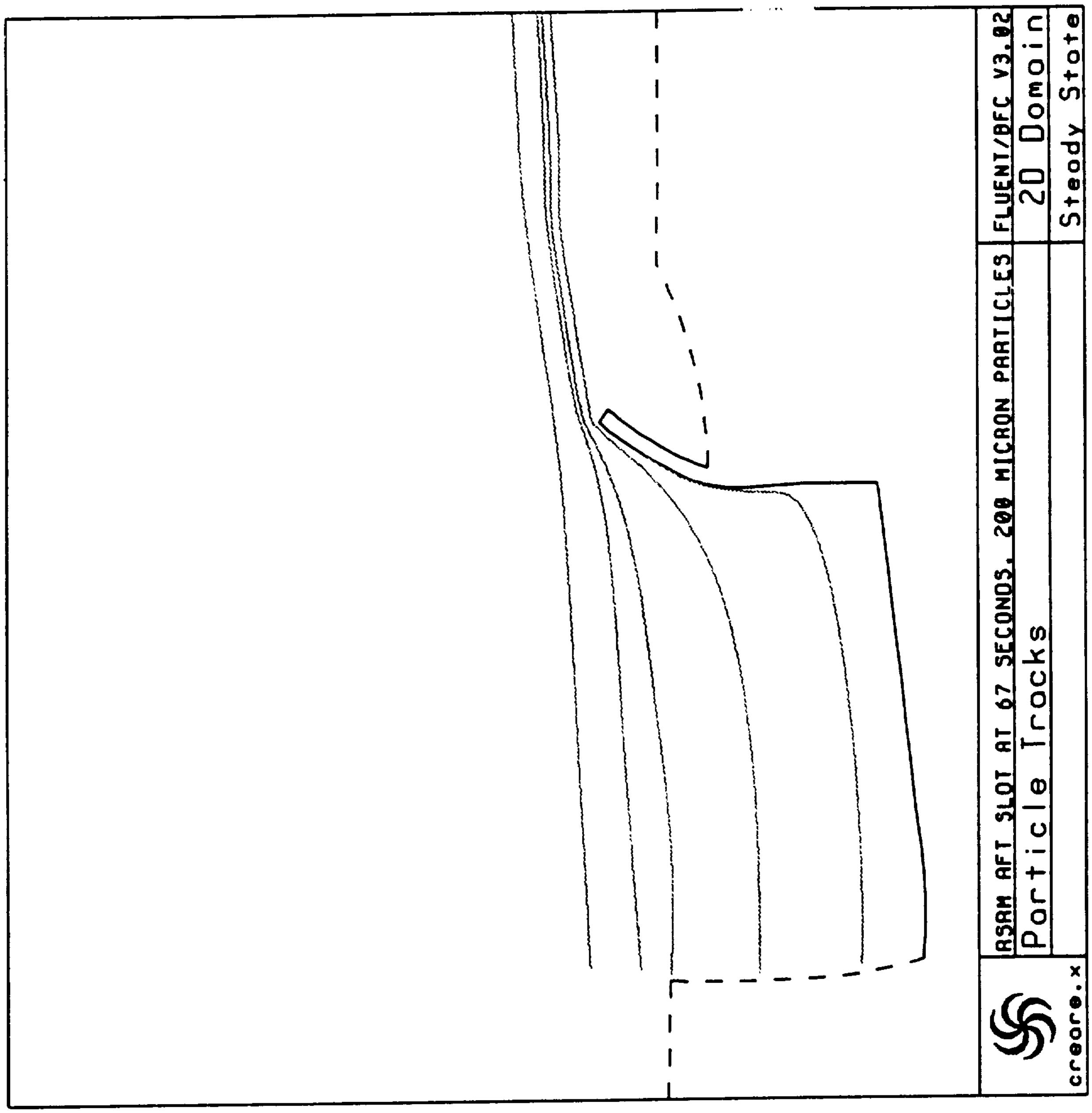
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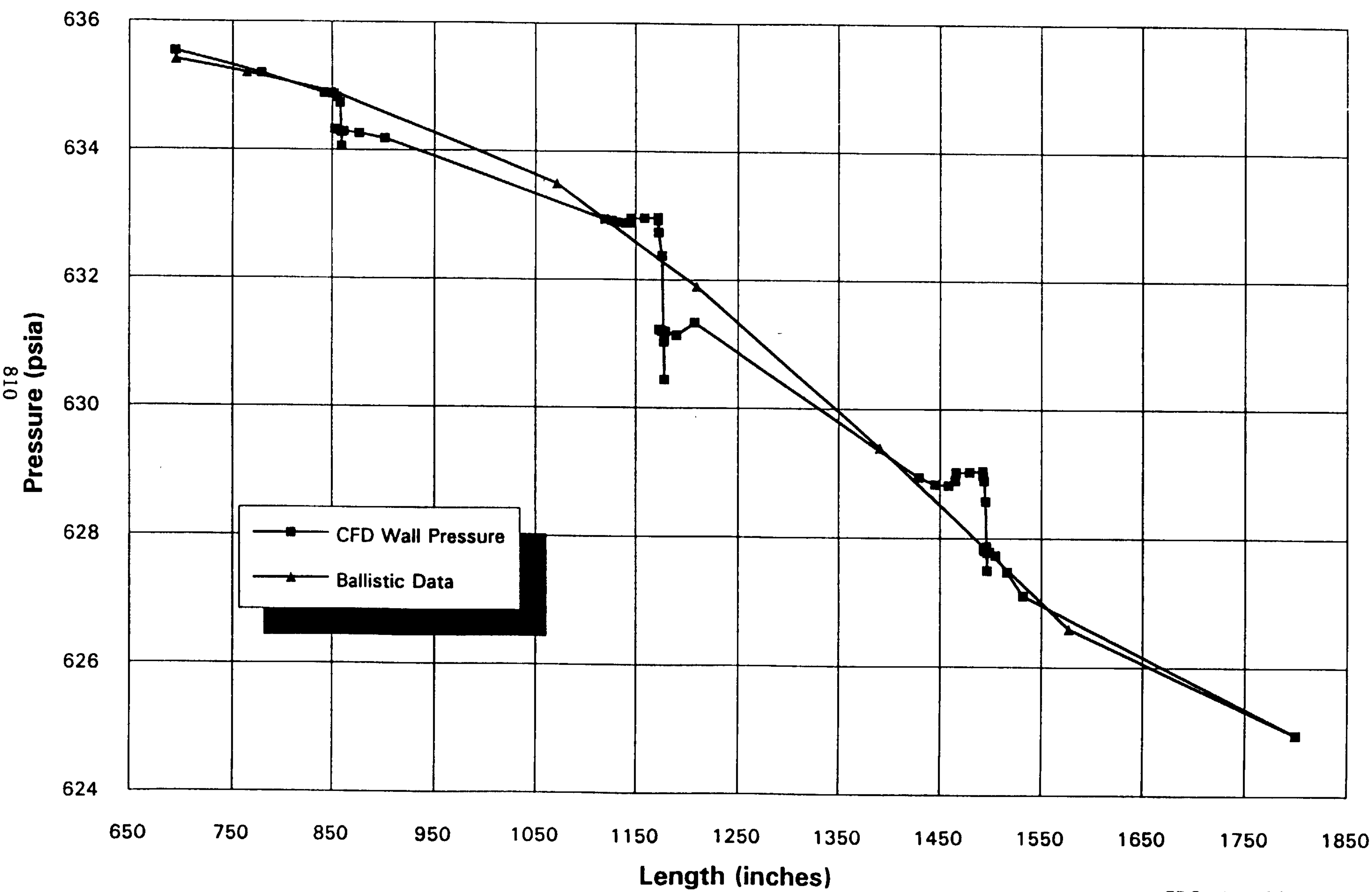
FLUENT/BFC V3.02
Particle Tracks
2D Domain
Steady State
creare.x

RSRM Motor Pressure at 67 Seconds



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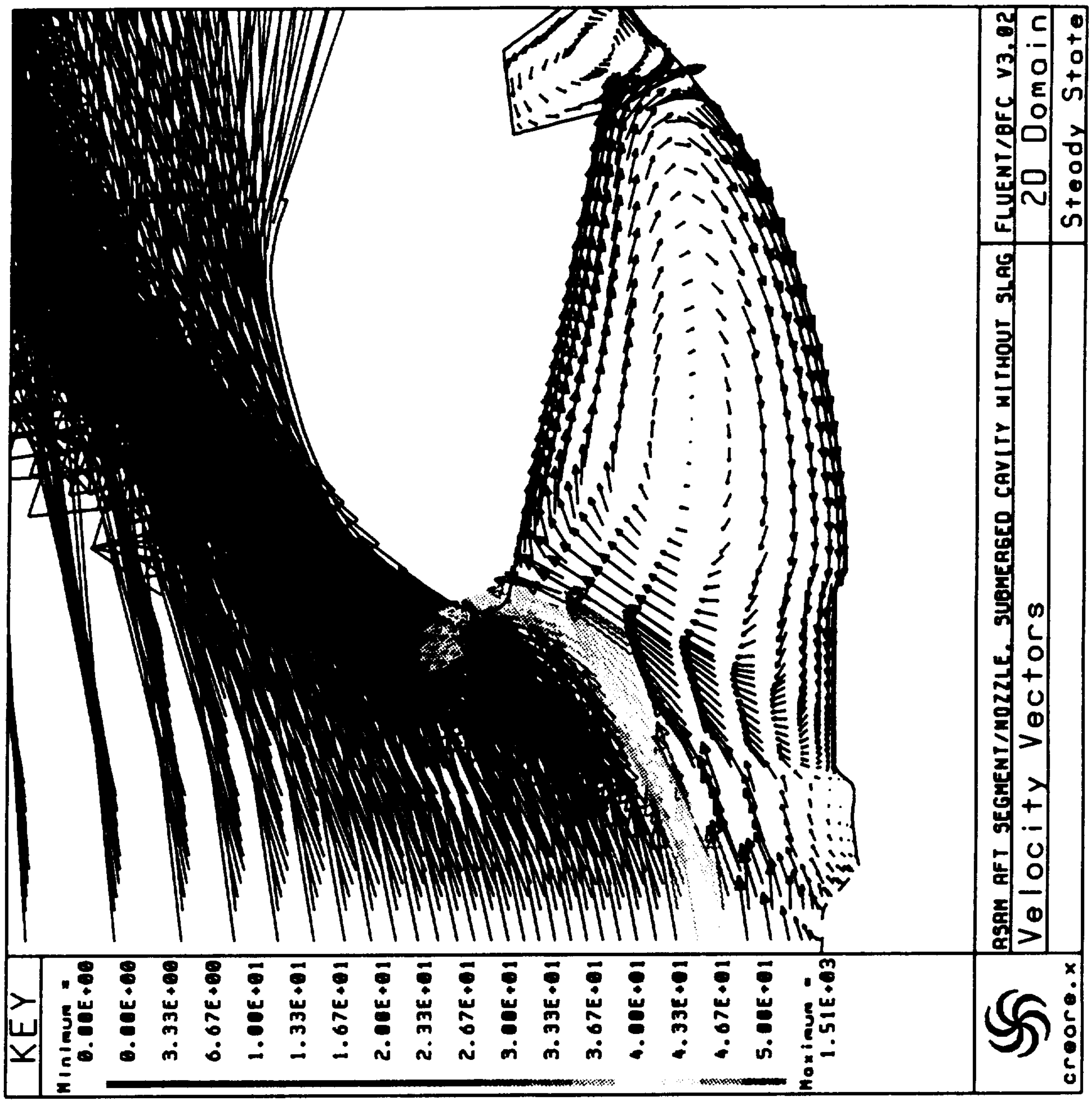
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2D Domain
Steady State
Velocity Vectors
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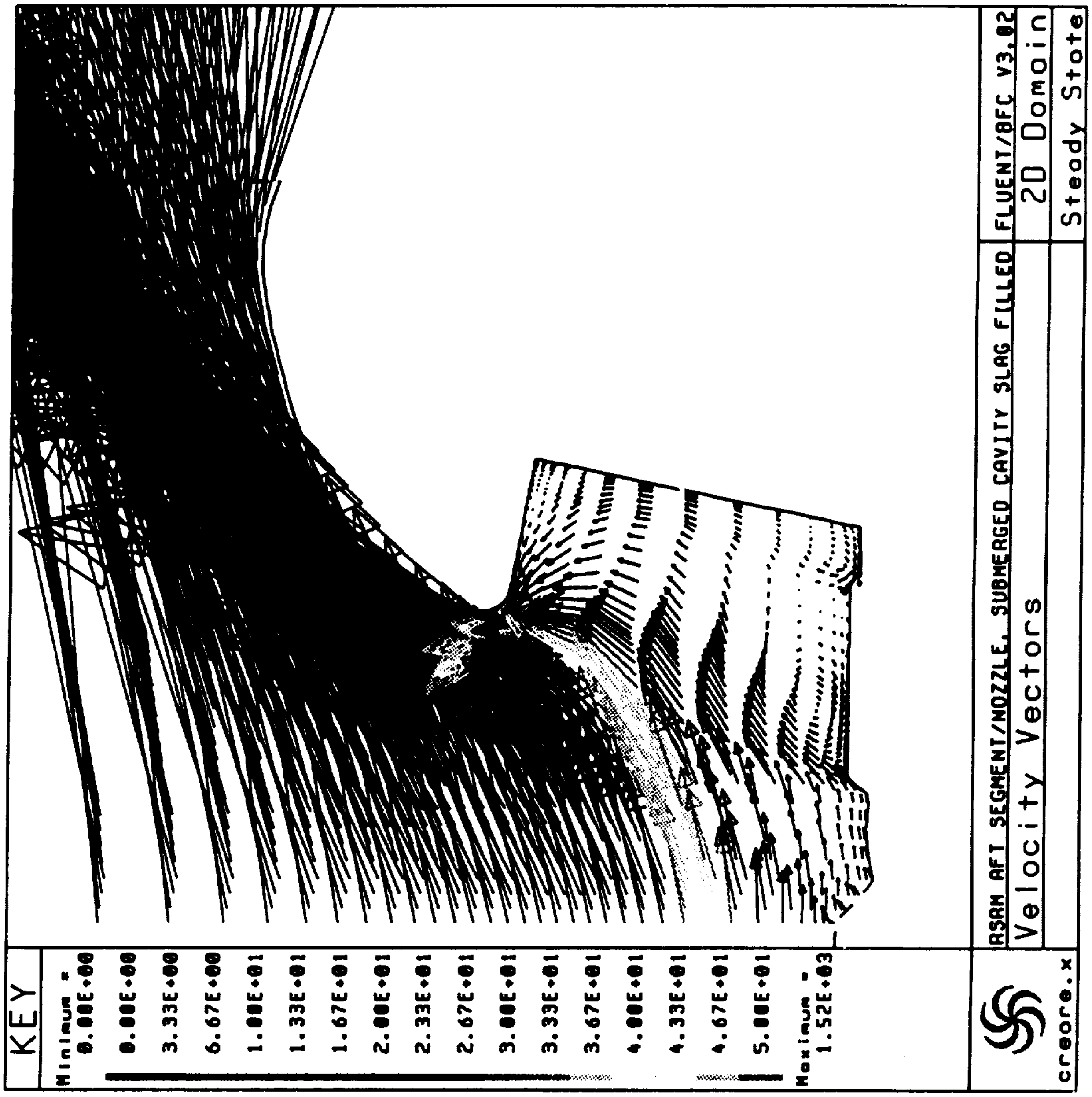
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Velocity Vectors
2D Domain
Steady State
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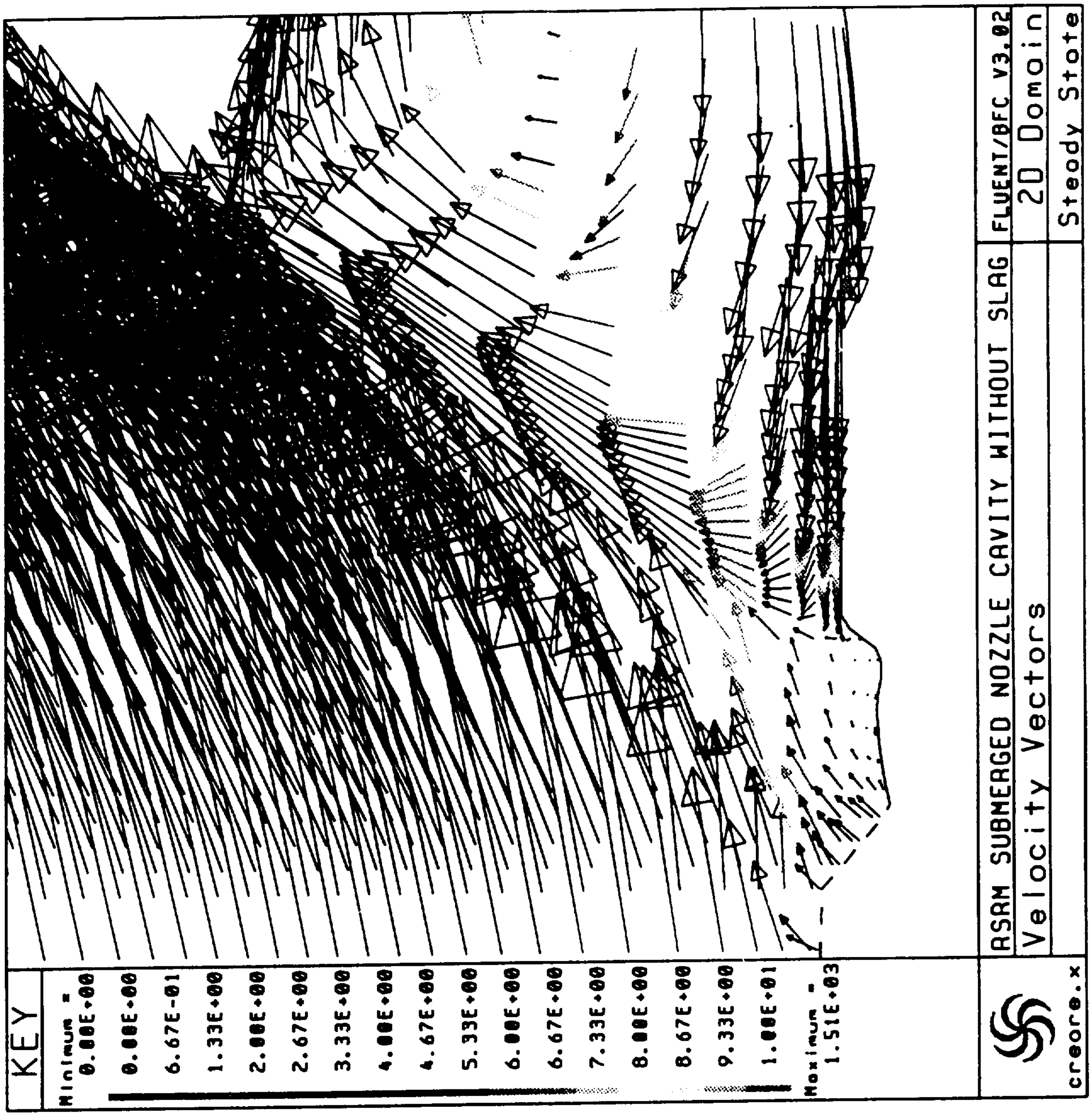

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Velocity Vectors
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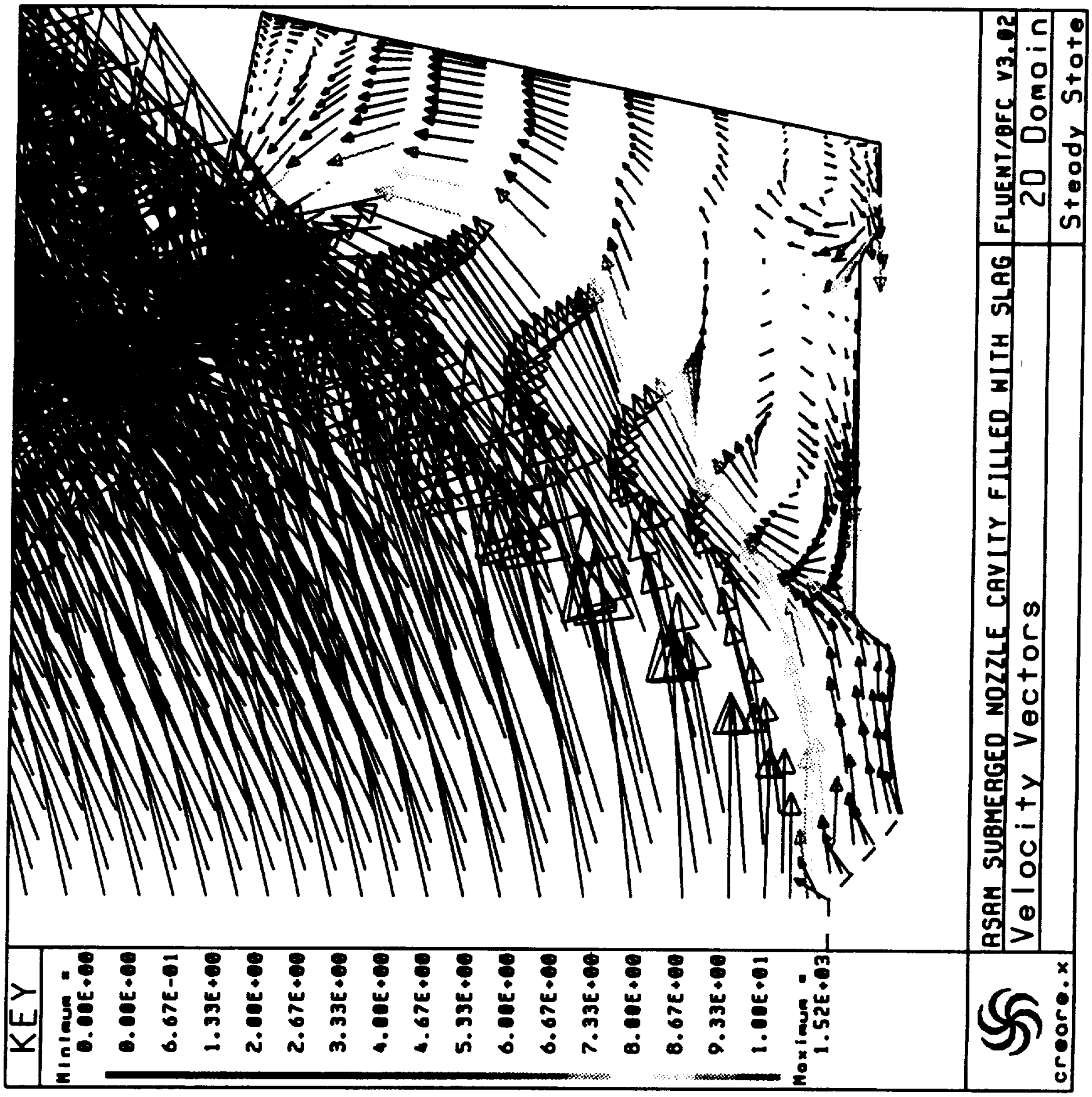
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ASAM SUBMERGED NOZZLE CAVITY FILLED WITH SLAG
FLUENT/BFC V3.02
Velocity Vectors
2D Domain
Steady State
creare.x

RSRM ANALYSIS CONCLUSIONS

- INHIBITOR PRESSURE LOADS WERE PROVIDED AND USED TO DETERMINE CASTABLE INHIBITOR LOADS, DEFORMATION, AND FAILURE MECHANISMS

- AFT CASE FLOW FIELD SOLUTION OFFERED EXPLANATION OF ABNORMAL EROSION PATTERN AND SLAG EXPULSION MECHANISM

- PARTICLE TRAJECTORY ANALYSIS SHOWED PROPENSITY FOR COLLECTING SLAG GREATEST AT CENTER SLOT

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ASRM ANALYSIS OBJECTIVES

- DEFINE INTERNAL MOTOR FLOW ENVIRONMENT TO SUPPORT OVERALL MOTOR DESIGN EFFORT
- PROVIDE AXIAL MOTOR PORT PRESSURE GRADIENTS TO SUPPORT PERFORMANCE ANALYSIS AND TO PROVIDE PROPELLANT PRESSURE LOADS
- PROVIDE DETAILED TWO-DIMENSIONAL PRESSURE GRADIENTS AROUND JOINT SLOTS TO DETERMINE PROPELLANT DEFORMATIONS THROUGH AN INTERACTIVE CFD/STRUCTURAL ANALYSIS
- CALCULATE DEVELOPMENT OF VELOCITY PROFILES DOWN MOTOR PORT TO IDENTIFY TRANSITION AS IT MAY RELATE TO EROSIVE BURNING

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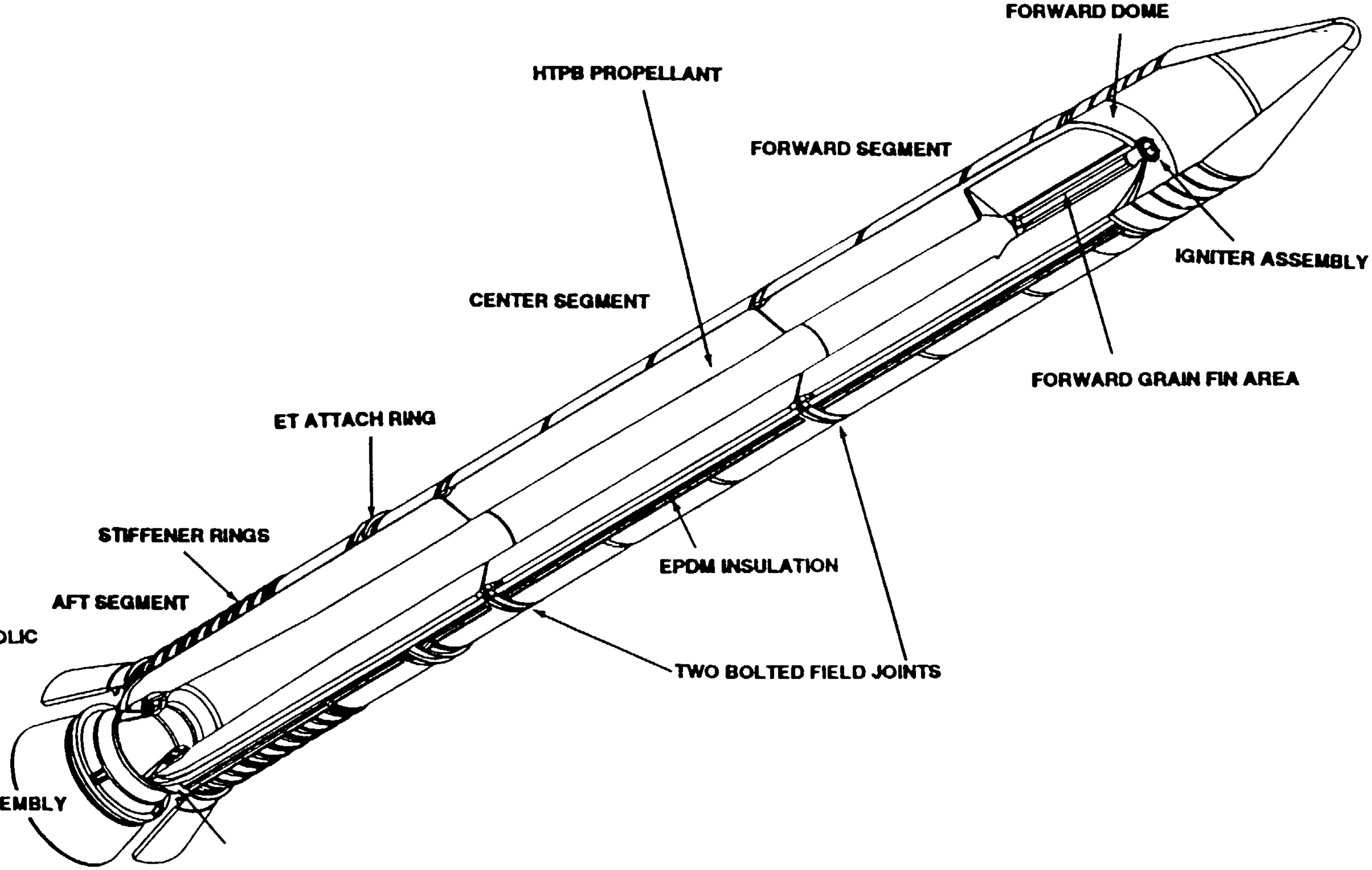
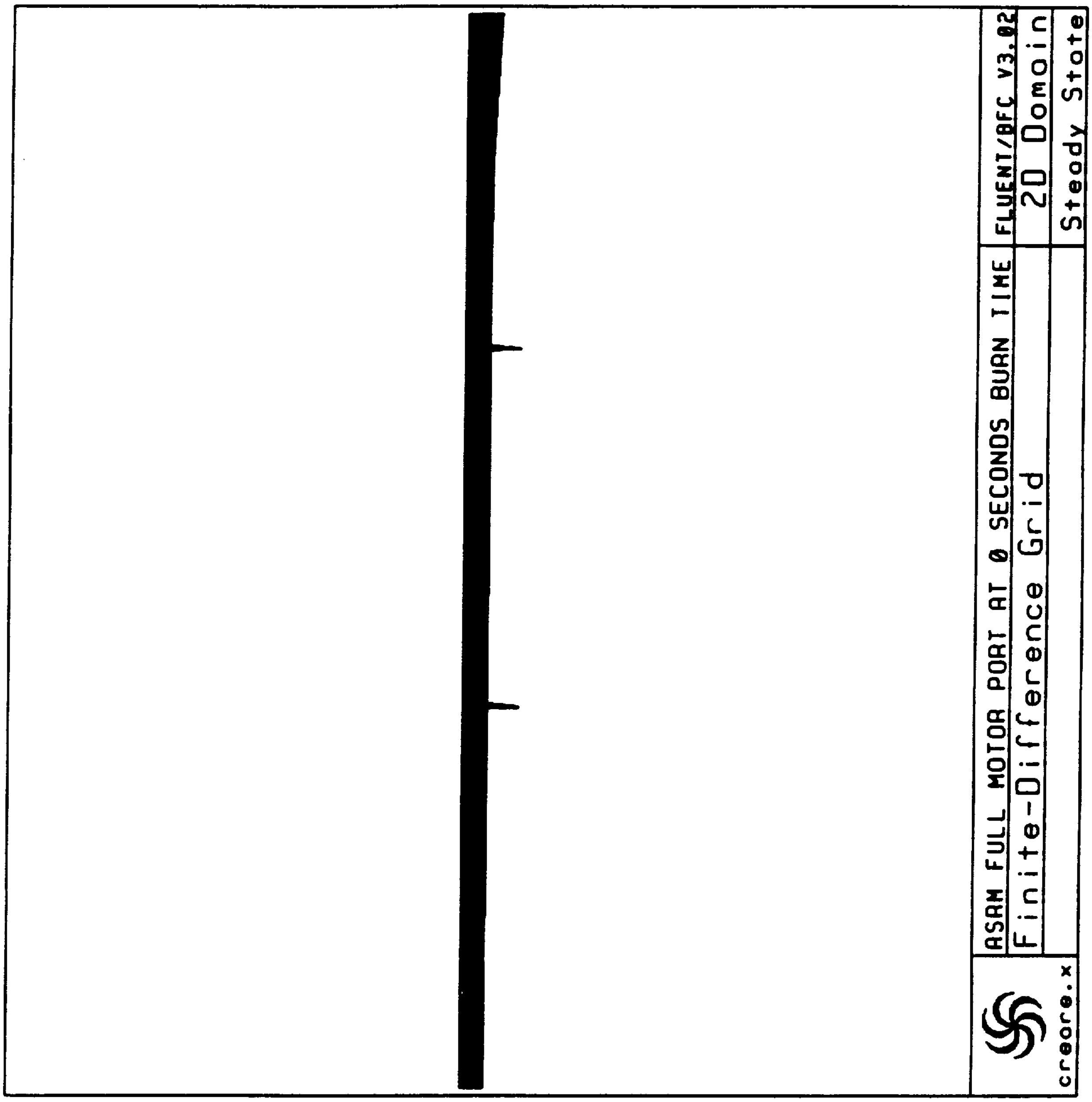
ASRM
LOCKHEED • AEROJET • RUST

THE ASRM

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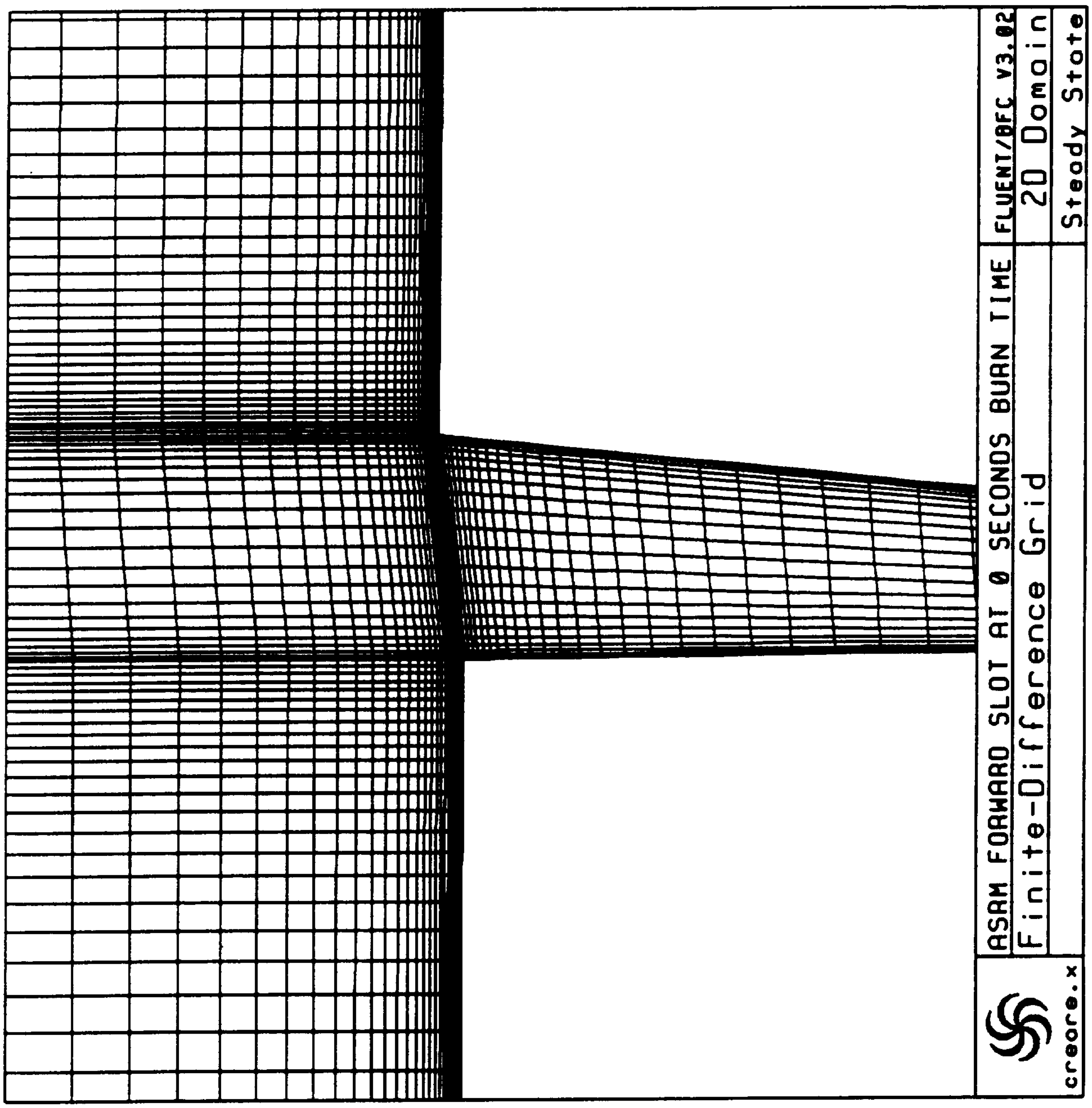
FLUENT/BFC V3.02
Finite-Difference Grid
2D Domain
Steady State
creare.x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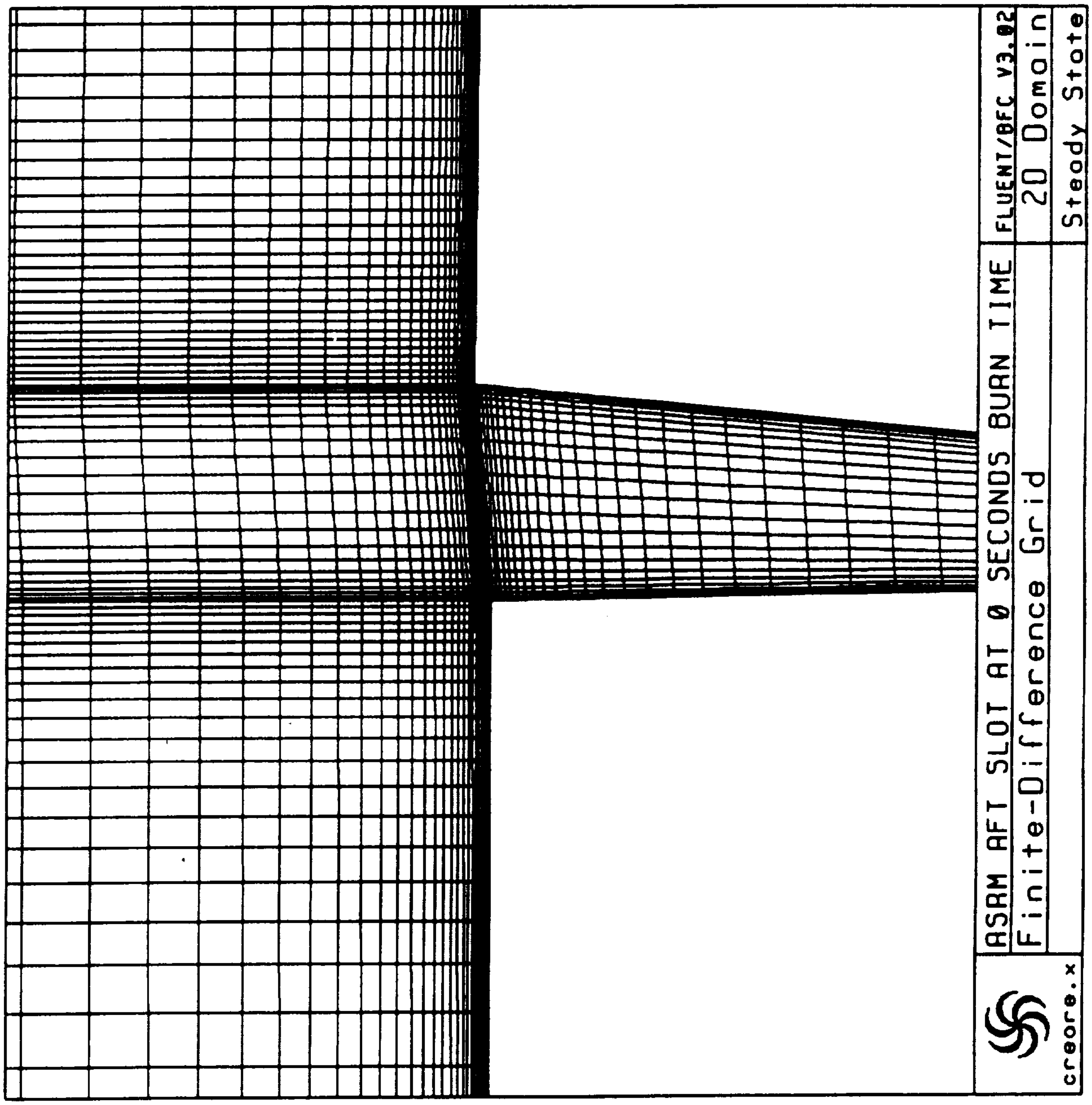
ASRM AFT SLOT AT 0 SECONDS BURN TIME
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2D Domain
Steady State
creare.x

ASRM MOTOR BOUNDARY CONDITIONS

0 SECOND MOTOR BURN TIME CONFIGURATION

MOTOR AFT SEGMENT END OF GRAIN PRESSURE	788 psia
TOTAL TEMPERATURE	6345°R
SPECIFIC HEAT RATIO	1.128
DYNAMIC VISCOSITY	6.34 X 10^{-5} lbm/ft-sec
MOLECULAR WEIGHT OF EQUIVALENT GAS	29.489
$\dot{M}$ FORWARD SEGMENT STAR GRAIN	5501 lbm/sec
$\dot{M}$ FORWARD SEGMENTS C. P.	1428 lbm/sec
$\dot{M}$ CENTER SEGMENT	2326 lbm/sec
$\dot{M}$ AFT SEGMENT	2415 lbm/sec

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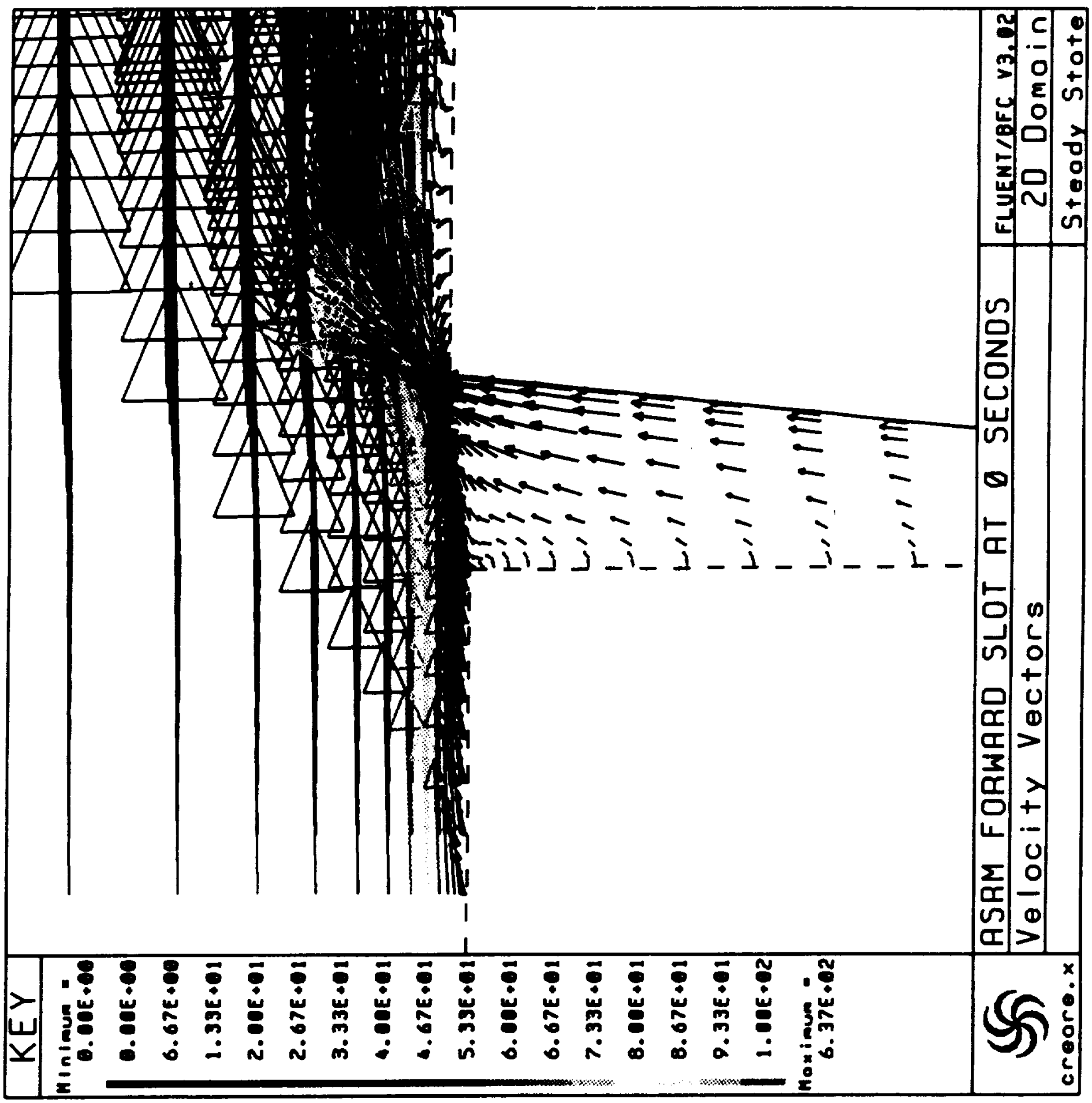
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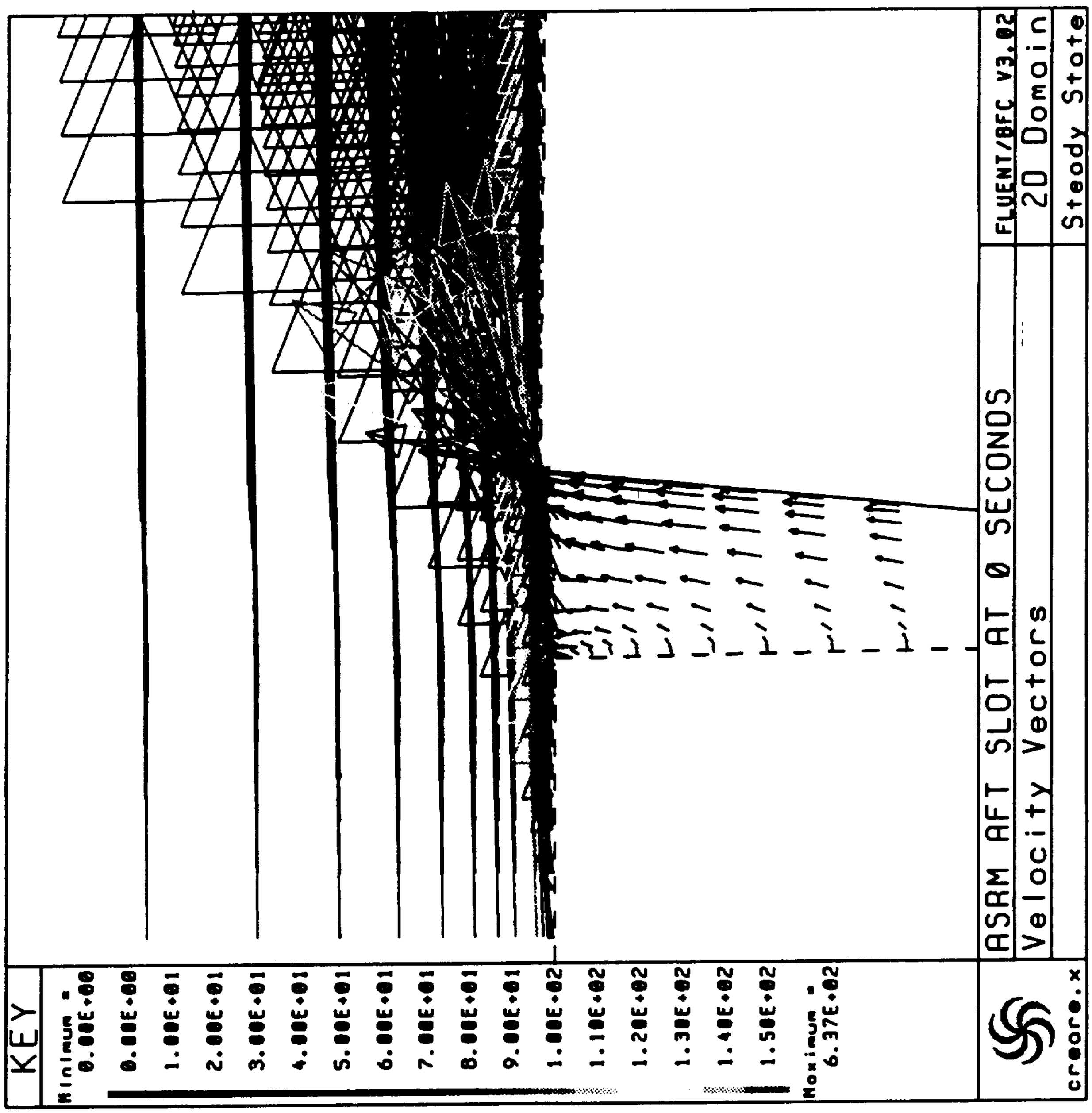
ASRM FORWARD SLOT AT Ø SECONDS
Velocity Vectors
FLUENT/BFC V3.02
2D Domain
Steady State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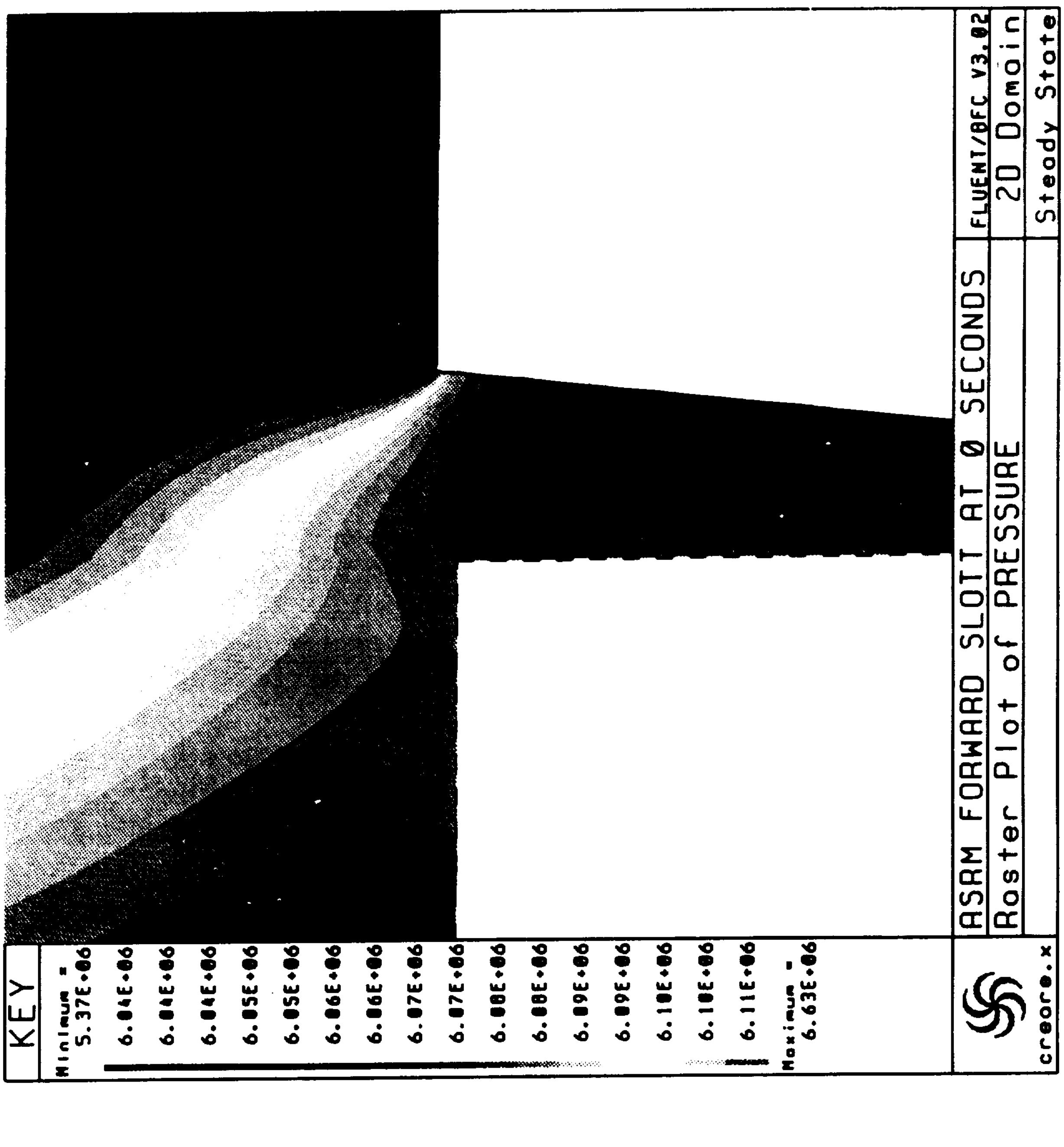
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Raster Plot of PRESSURE
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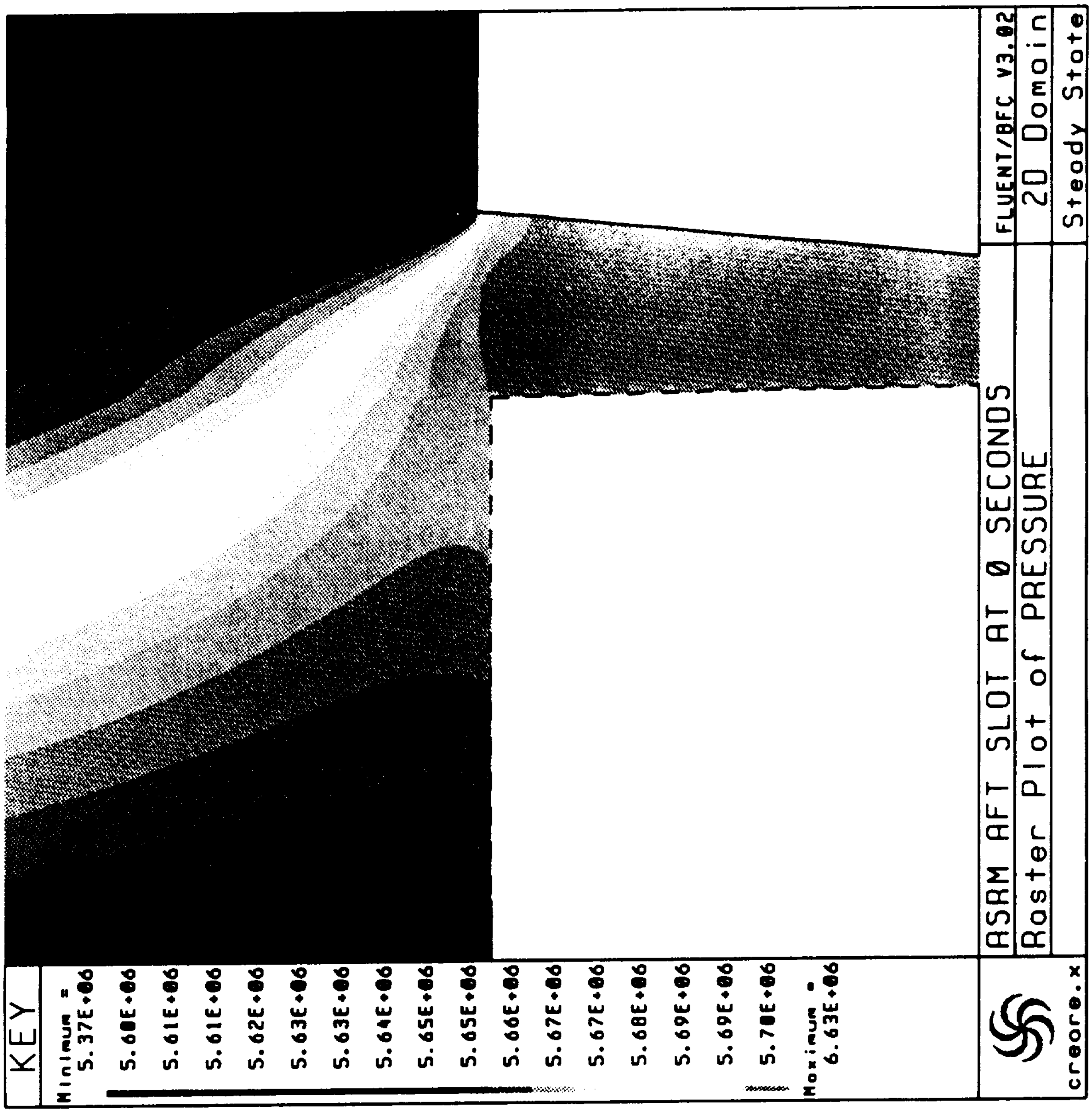
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ASRM AFT SLOT AT 0 SECONDS
Raster Plot of PRESSURE
FLUENT/BFC V3.02
2D Domain
Steady State
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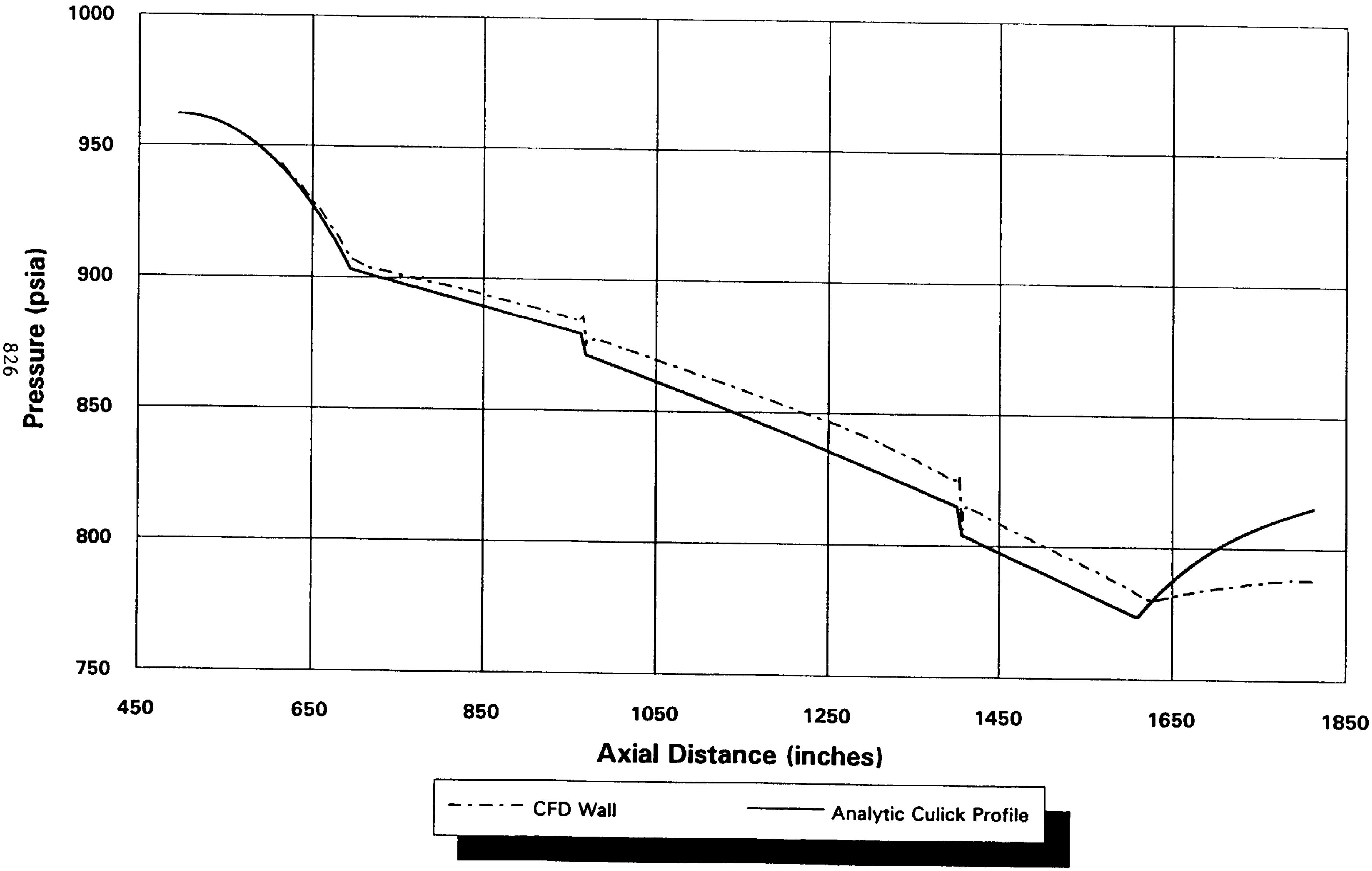
ASRM Full-Scale Motor Static Pressure

Adjusted k-e Model



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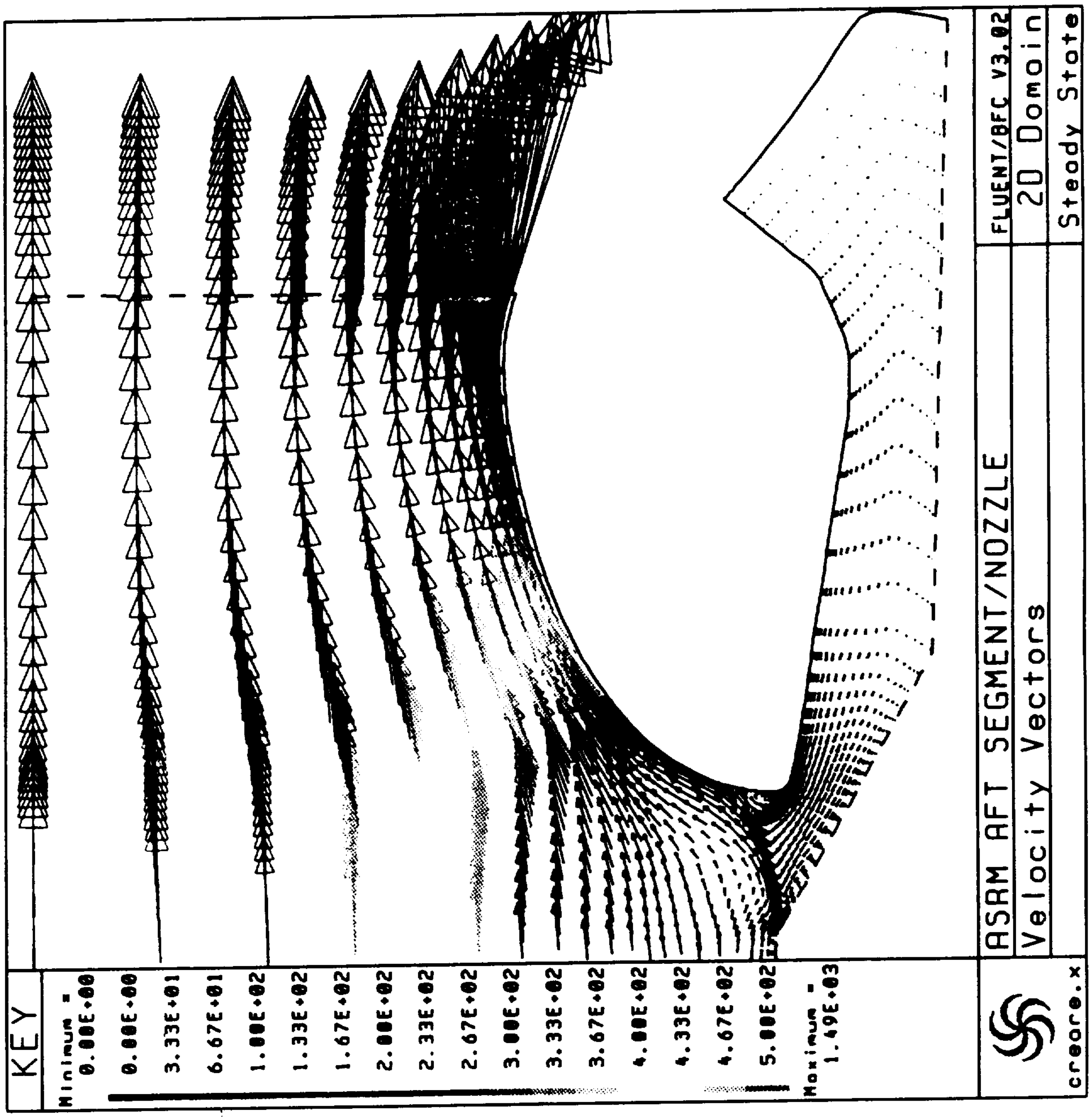
ASRM AFT SEGMENT/NOZZLE
Velocity Vectors
FLUENT/BFC V3.02
2D Domain
Steady State
creare.x
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0.00E+00
3.33E+01
6.67E+01
1.00E+02
1.33E+02
1.67E+02
2.00E+02
2.33E+02
2.67E+02
3.00E+02
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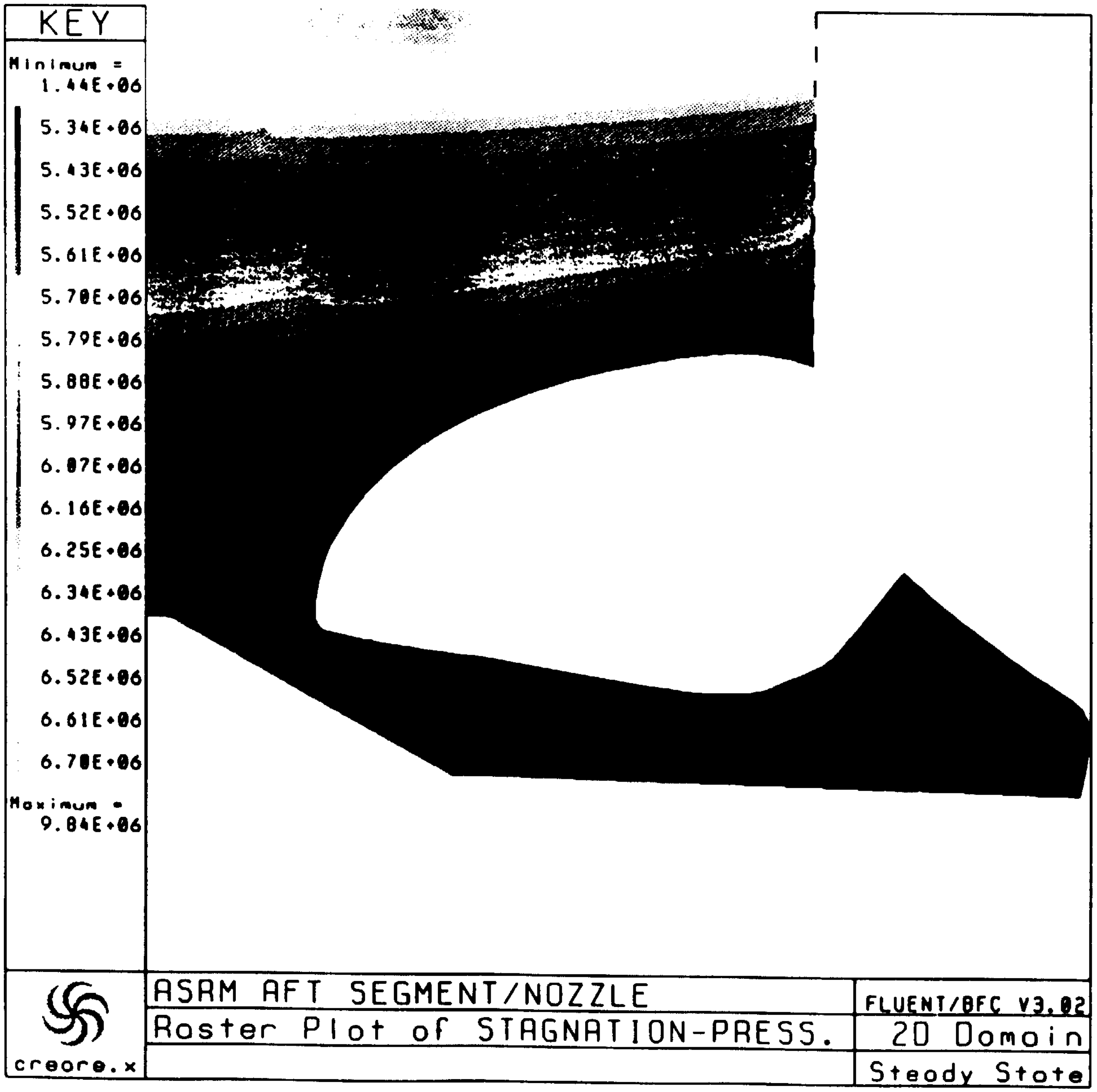
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6.07E+06
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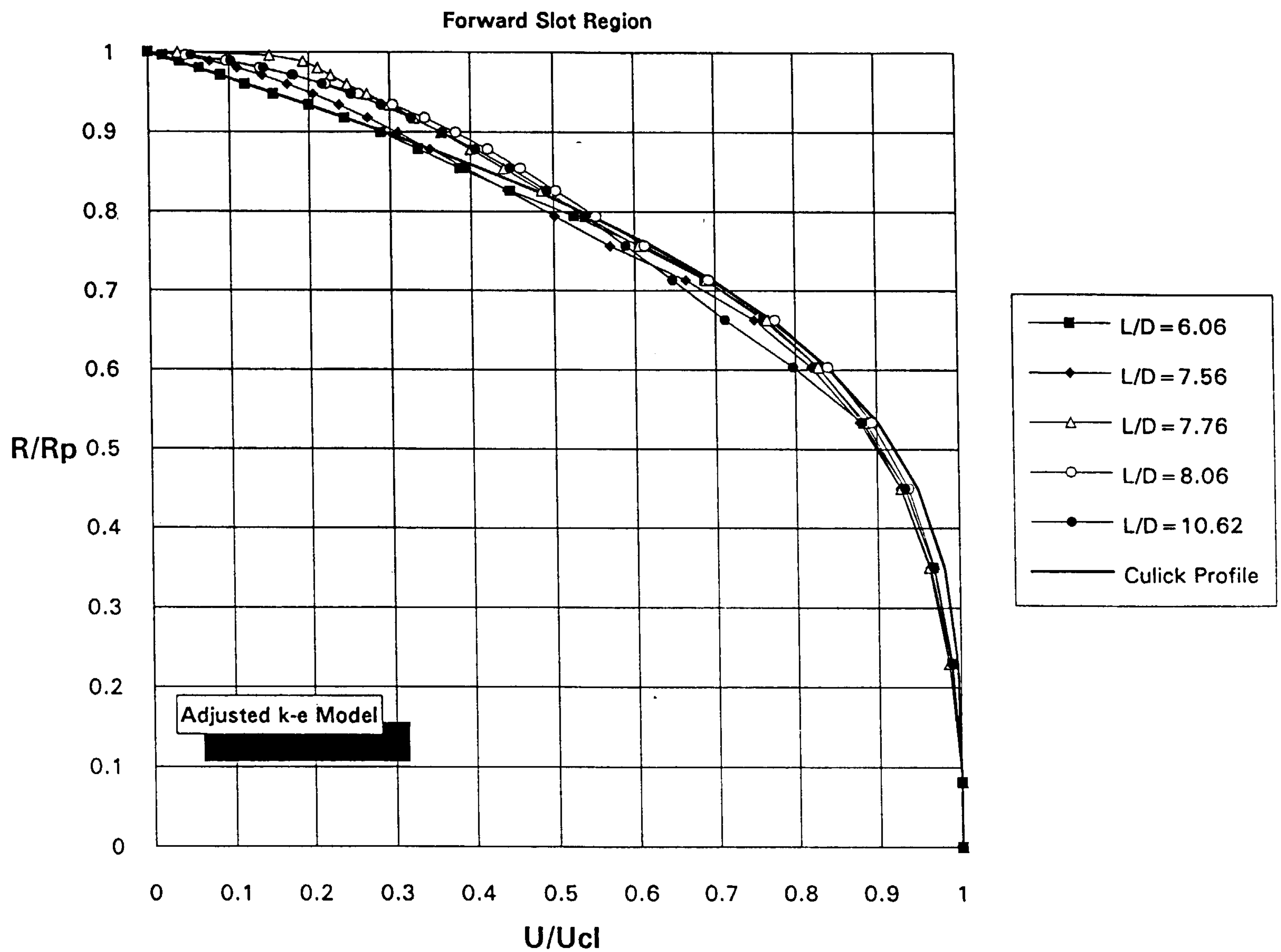
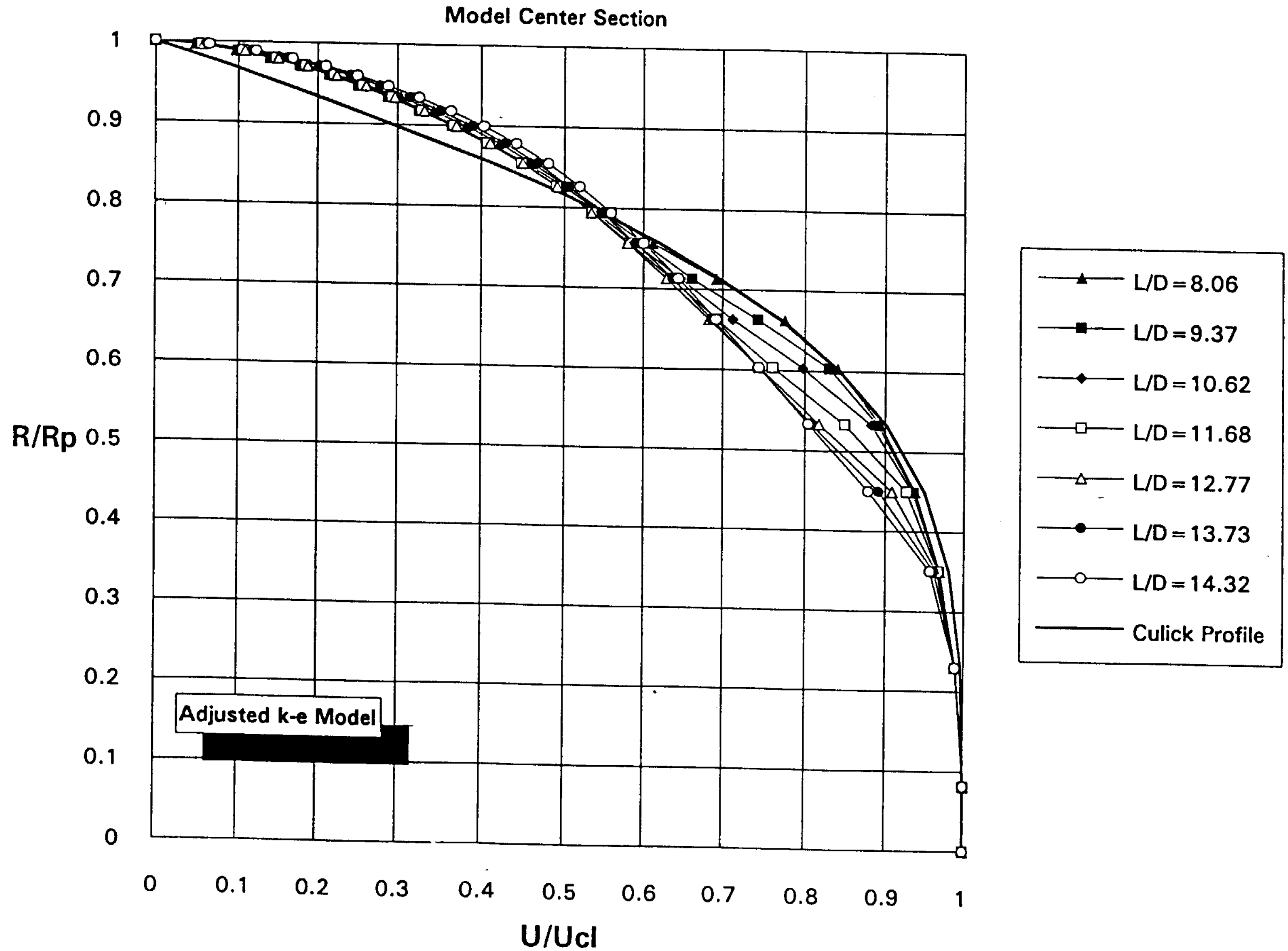
6.34E+06
6.43E+06
6.52E+06
6.61E+06
6.70E+06
Maximum =
9.84E+06
creare.x
ASRM AFT SEGMENT/NOZZLE
Raster Plot of STAGNATION-PRESS.
FLUENT/BFC V3.02
2D Domain
Steady State

ASRM Full-Scale Motor Velocity Profiles



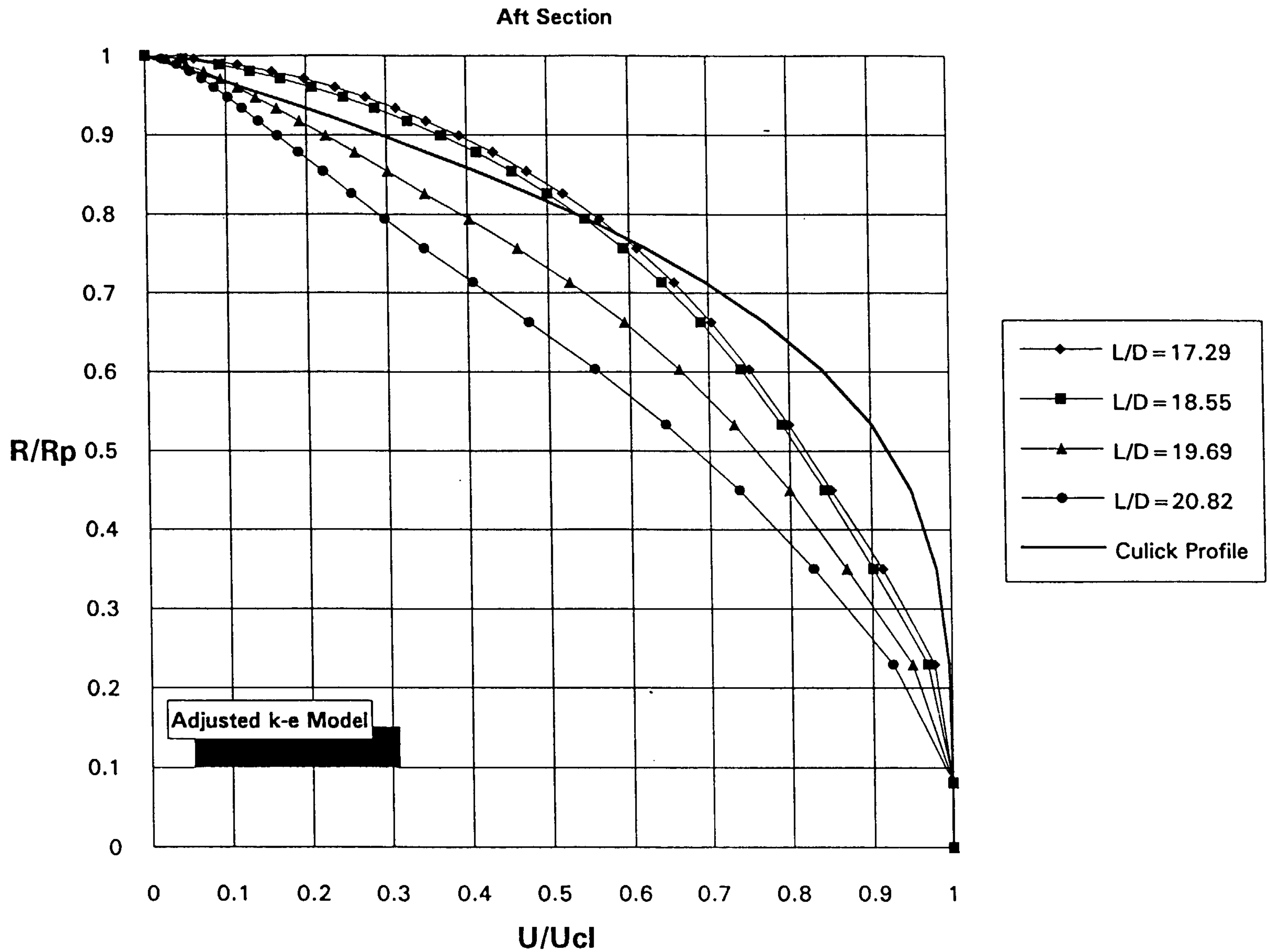
ERCI 07/06/92

ASRM Full-Scale Motor Velocity Profiles

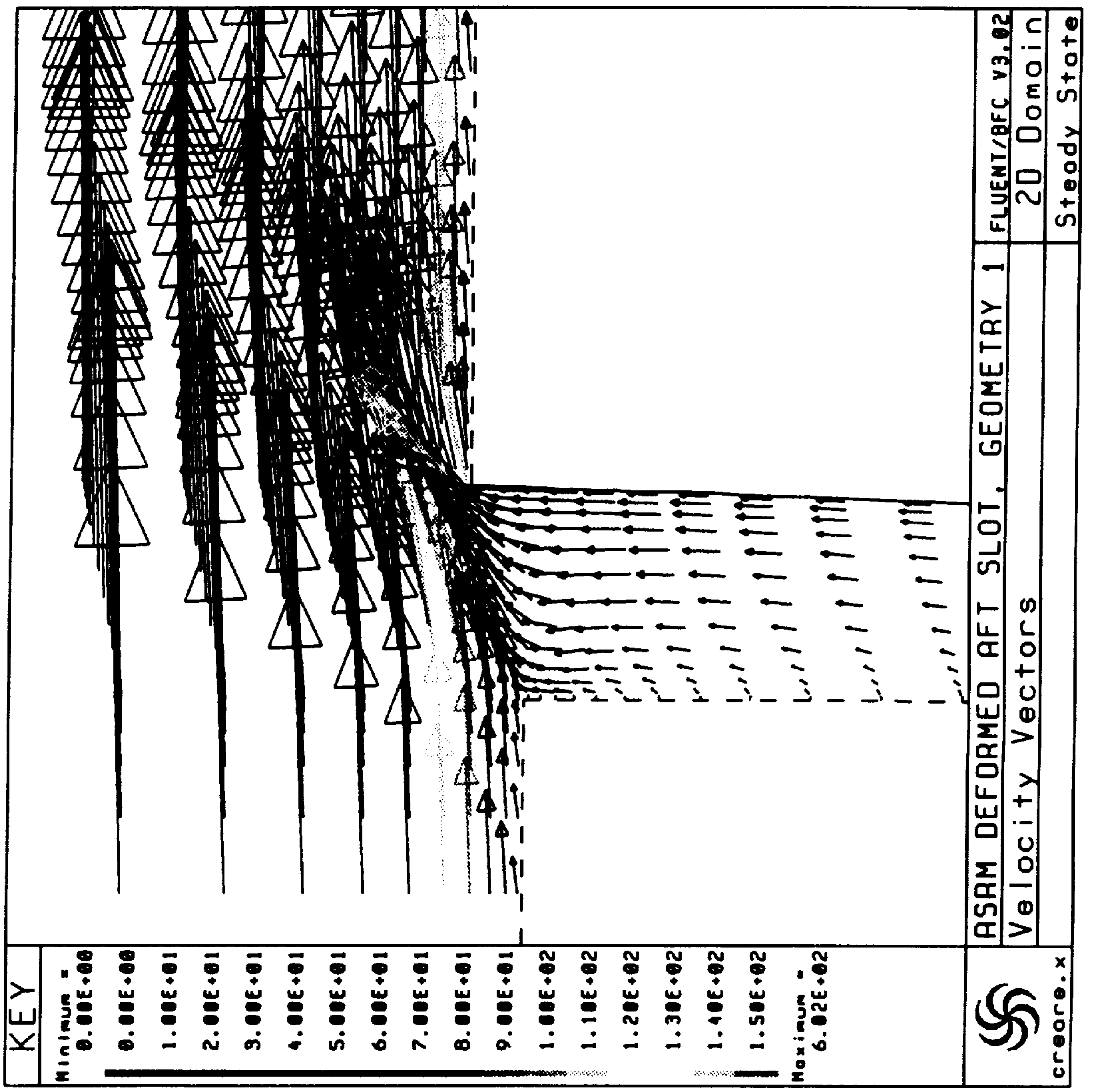


ERCI 07/06/92

ASRM Full-Scale Motor Velocity Profiles



ERCI 07/14/92



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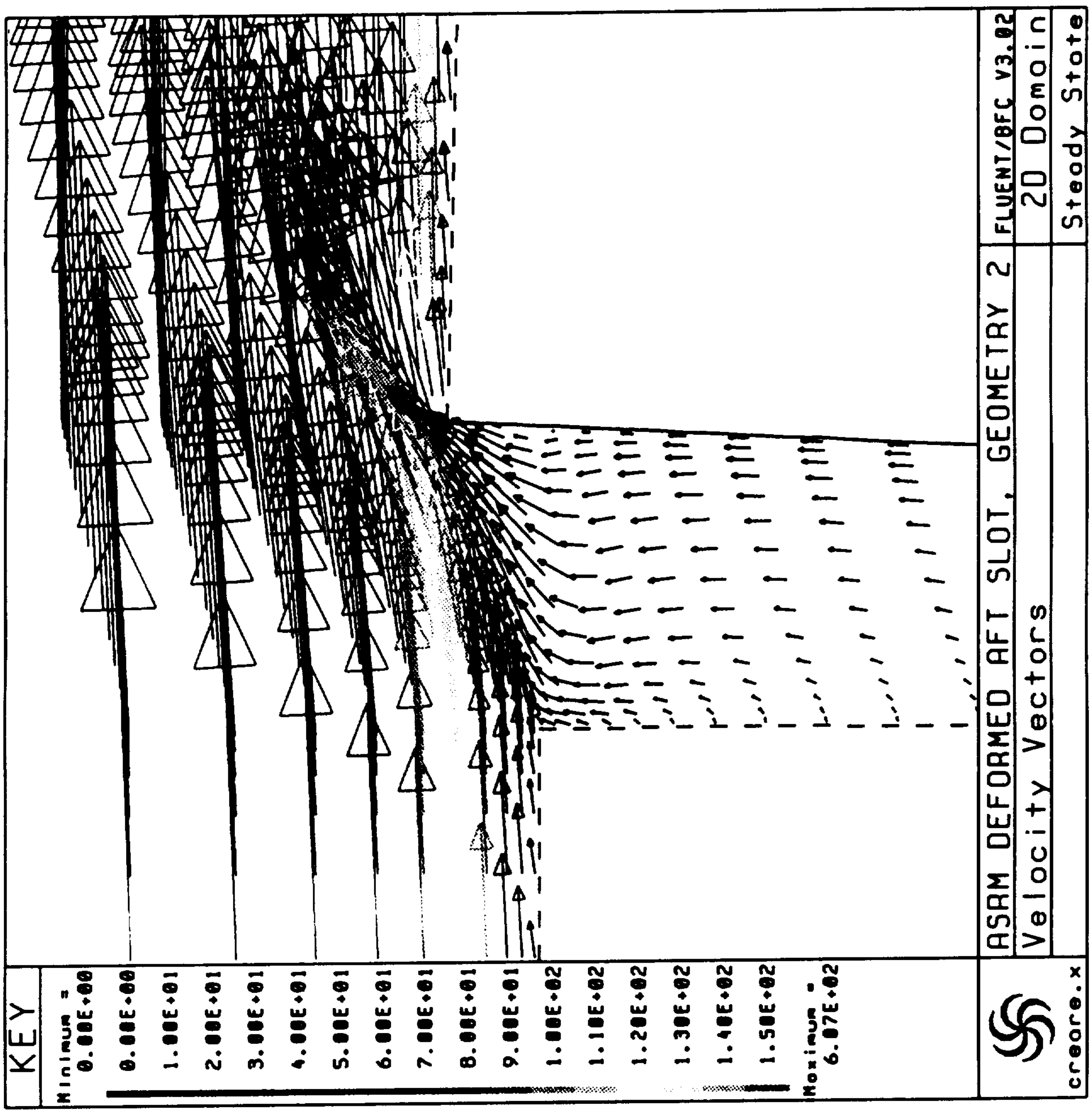
6.00E+01
7.00E+01
8.00E+01
9.00E+01
1.00E+02
1.10E+02
1.20E+02
1.30E+02
1.40E+02
1.50E+02
Maximum = 6.02E+02
ASRM DEFORMED AFT SLOT, GEOMETRY 1
FLUENT/BFC V3.02
Velocity Vectors
2D Domain
Steady State
creare.x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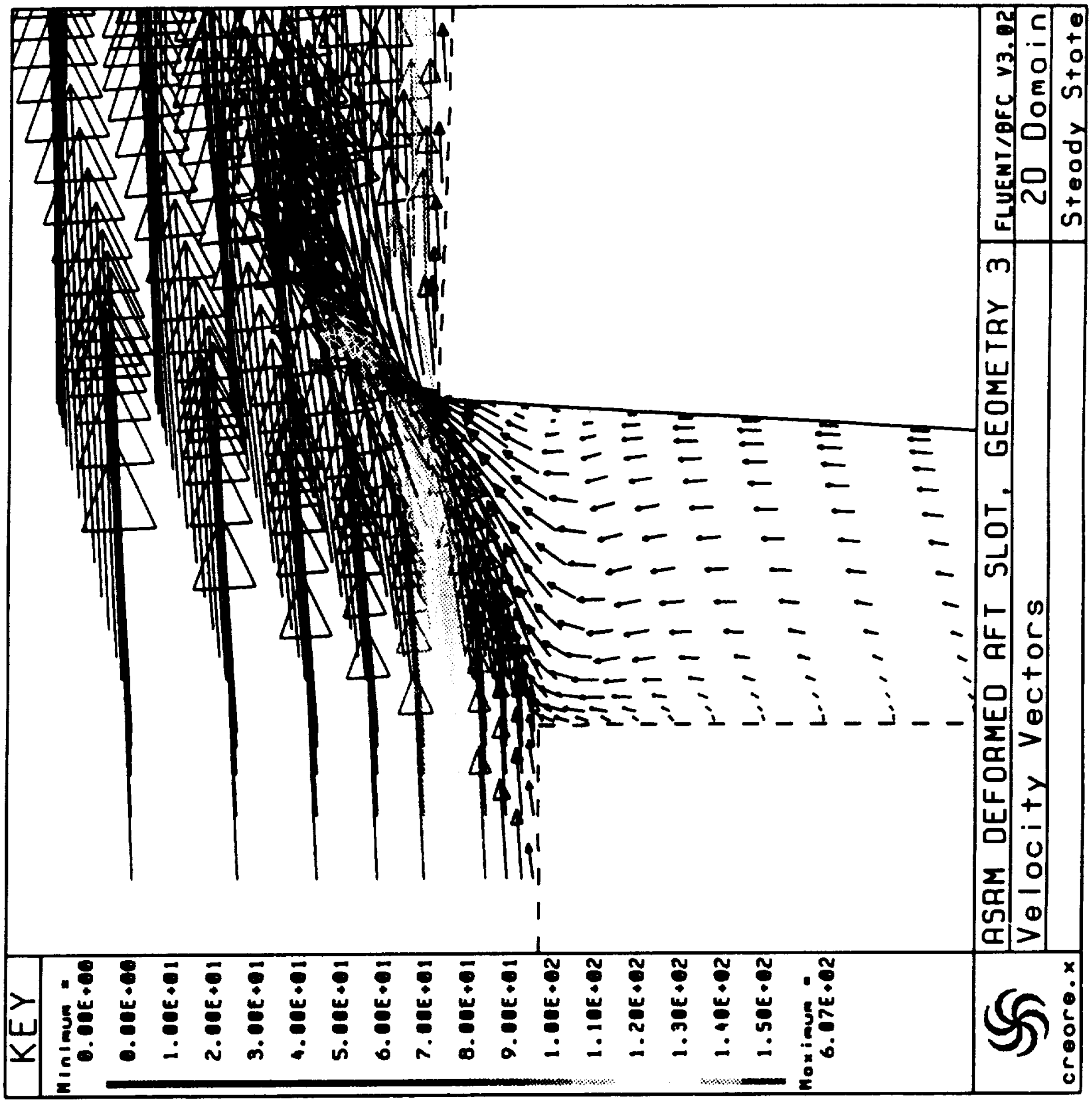
7.00E+01
8.00E+01
9.00E+01
1.00E+02
1.10E+02
1.20E+02
1.30E+02
1.40E+02
1.50E+02
Maximum = 6.07E+02
ASRM DEFORMED AFT SLOT, GEOMETRY 2
Velocity Vectors
FLUENT/BFC V3.02
2D Domain
Steady State
creare.x


ASRM DEFORMED AFT SLOT, GEOMETRY 3
Velocity Vectors
FLUENT/BFC V3.02
2D Domain
Steady State
KEY
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3.00E+01
4.00E+01
5.00E+01
6.00E+01
7.00E+01
8.00E+01
9.00E+01
1.00E+02
1.10E+02
1.20E+02
1.30E+02
1.40E+02
1.50E+02
Maximum = 6.07E+02
creare.x

ASRM ANALYSIS CONCLUSIONS

- MOTOR PORT PRESSURE GRADIENTS FROM CFD ANALYSES HAVE PROVIDED ADDITIONAL PERFORMANCE INFORMATION AND TEST DATA INTERPRETATION

- A SIGNIFICANT PORTION OF THE PROPELLANT DEFORMATION AT THE AFT SLOT IS DUE TO 2-D FLOW EFFECTS

- VELOCITY PROFILE TRANSITION ZONE AND EFFECT OF BORE GEOMETRY FLARE WAS PREDICTED BY CFD ANALYSIS

ERC, Inc.
4/21/93