SHUTTLE DATA BOOK
SRM FRAGMENT VELOCITY MODEL

PRESENTED TO THE
SRB FRAGMENT MODEL REVIEW PANEL

This report was prepared for the Jet Propulsion Laboratory,
California Institute of Technology, sponsored by the
National Aeronautics and Space Administration.

2 MARCH 1989
NASA HEADQUARTERS
WASHINGTON, D.C.

BRIEFER:
M.B. ECK
INTRODUCTION

- THE STUDY DESCRIBED IN THIS BRIEFING WAS UNDERTAKEN TO DETERMINE THE VELOCITY OF FRAGMENTS GENERATED BY THE RANGE SAFETY DESTRUCTION (RSD) OR RANDOM FAILURE OF A SPACE TRANSPORTATION SYSTEM (STS) SOLID ROCKET MOTOR (SRM).

- LARGE, HIGH VELOCITY SRM FRAGMENTS WERE OBSERVED TO HAVE BEEN GENERATED IN THE STS-51L (CHALLENGER) EVENT.

- THE SPECIFIC REQUIREMENT OF THIS STUDY WAS TO PROVIDE A FRAGMENT MODEL FOR USE IN THOSE GALILEO AND ULYSSES RTG SAFETY ANALYSES CONCERNED WITH POSSIBLE FRAGMENT IMPACT ON THE SPACECRAFT RADIOISOTOPE THERMOELECTRIC GENERATORS (RTGS).

THIS MORNING'S BRIEFING IS DIVIDED INTO TWO MAJOR SECTIONS:

- MODEL DEVELOPMENT AND APPLICATION

- MODEL REVIEW AND BOUNDARY ASSUMPTION VERIFICATION

- A CRITIQUE OF AN SRM FRAGMENT VELOCITY MODEL DEVELOPED BY PERSONNEL AT THE NAVAL SURFACE WARFARE CENTER (NSWC) WILL BE THE SUBJECT OF THIS AFTERNOON'S BRIEFING.
RTG LOCATIONS FOR GALILEO AND ULYSSES SPACECRAFT LAUNCH BY SPACE SHUTTLE

1/200TH SCALE
REVISED 1/76

RTG LOCATIONS
ULYSSES AT
$X_0 = 922, Y_0 = 0, Z_0 = 453$

GALILEO AT
$X_0 = 999, Y_0 = 161, Z_0 = 430$

LOCATION OF SRB STEEL CASE SEGMENTS

WING AND MID FUSELAGE CROSS SECTIONS
$X_0 = 800$
$X_0 = 1000$
$X_0 = 1200$
## INTRODUCTION (CONT’D)
MORNING BRIEFING ORGANIZATION

<table>
<thead>
<tr>
<th>I. Model Development and Application</th>
<th>II. Model Review and Boundary Assumption Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>• What We Did, Why We Did It, and What Resulted.</td>
<td>• Sanity Checks—Special Analyses Used to Verify the Original Modeling Approach.</td>
</tr>
<tr>
<td>• Study Objectives</td>
<td>• Unit-Length Energy/Mass Ratios</td>
</tr>
<tr>
<td>• Reprise of the Physical Evidence</td>
<td>• One and Two Chamber Flow Models Using Rigid Body Assumptions</td>
</tr>
<tr>
<td>• Physical Evidence Implications</td>
<td>• Effects of 3D flow and Fragment Rotation Using Rigid Body Analyses</td>
</tr>
<tr>
<td>• Required Model Attributes</td>
<td>• New, Detailed Model Used to Assess:</td>
</tr>
<tr>
<td>• Model Development</td>
<td>- PBAN Grain and Bond Strength Effects</td>
</tr>
<tr>
<td>• Model Results</td>
<td>- PBAN Material Properties: Effects of High Strain Rates</td>
</tr>
<tr>
<td>• Comparison of Model Results to Observations</td>
<td>- PBAN Crack Initiation and Propagation</td>
</tr>
</tbody>
</table>
STUDY OBJECTIVES

- THE STUDY DESCRIBED IN THIS BRIEFING HAD THE FOLLOWING DETAILED OBJECTIVES:

  - PREDICT SRM FRAGMENT VELOCITY OVER THE ENTIRE MISSION ELAPSED TIME (MET) DOMAIN FOR BOTH RANDOM AND RSD FAILURES.

  - PREDICT SRM FRAGMENT AZIMUTH OVER THE MET RANGE FOR RANDOM AND RSD FAILURES.

  - PREDICT SRM FRAGMENT ROTATION RATE OVER THE MET RANGE FOR RANDOM AND RSD FAILURES.

  - PERFORM A LARGE NUMBER OF PARAMETRIC SENSITIVITY ANALYSES TO DETERMINE THE STATISTICAL DISTRIBUTION OF PROBABLE FRAGMENT ENVIRONMENTS RESULTING FROM STS-SRM RANDOM OR RSD FAILURE.

  - THE RESULTS OBTAINED USING THE METHODS DEVELOPED WERE TO BE CONSISTENT WITH ALL AVAILABLE PHYSICAL EVIDENCE.
REPRISE OF THE SRM FRAGMENT VELOCITY PHYSICAL EVIDENCE

- TWO MAJOR SRM FAILURES OCCURRED IN EARLY 1986:
  - THE STS-51L AT 110 SECONDS MET
  - THE TITAN 34D-9 AT 10 SECONDS MET

- DETAILED STUDIES OF THE FILMS OF THESE EVENTS WERE UNDERTAKEN AS WERE ON-SITE INSPECTION OF ALL REMAINING PHYSICAL EVIDENCE.

- THE FOLLOWING IS AN ANECDOTAL COMPILATION FROM DIRECT PHYSICAL INSPECTION OF THE AVAILABLE EVIDENCE BY THE PARTICIPANTS IN THE MODELING EXERCISE TO BE DESCRIBED.

  - GRAIN (PBAN) DEBONDING WAS A COMMON FEATURE OF ALMOST ALL OF THE 34D-9 FRAGMENTS (EARLY MET FAILURE)

  - GRAIN DEBONDING WAS NOT A COMMON FEATURE OF THE STS-51L FRAGMENTS (LATE MET FAILURE WITH LESS THAN THREE INCHES OF FUEL REMAINING)
REPRISE OF THE SRM FRAGMENT VELOCITY PHYSICAL EVIDENCE (CONT'D)

- MOST CASING CRACKS ORIGINATED AND ENDED IN CLEVIS PIN HOLES. THIS WAS COMMON TO BOTH THE STS-51L AND 34D-9 EVENTS.

- FRAGMENTS FROM THE RANDOM FAILED 34D-9 MOTOR (SRM-2) SHOWED A DECREASE IN VELOCITY FROM SEGMENT 1 TO 4 (SEGMENT 1 FAILED FIRST).

- BOTH STS-51L SRMS WERE DESTROYED BY THE INITIATION OF A SINGLE 1000 GRAIN/FOOT HMX LINEAR SHAPED CHARGE (LSC).

- ONE 34D-9 SRM WAS DESTROYED BY THE INITIATION OF TWO 700 GRAIN/FOOT HMX LSCS SPACED TWO INCHES APART. THE OTHER 34D-9 SRM FAILED RANDOMLY IN SEGMENT 1.

- SOME OF THE DETAILED MAPS OF THE POST 34D-9 EVENT FRAGMENT LOCATIONS WHICH WERE PREPARED BY R AND D ASSOCIATES' PERSONNEL ARE PRESENTED IN THE FOLLOWING FOUR VUGRAPHS.
FRAGMENT ORIGIN AND LOCI GENERATED FROM THE RSD OF TITAN 34D-9 SRM1

Composite Loci of Cutline Fragments

Key

<table>
<thead>
<tr>
<th>Fragment No.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>538</td>
<td>1</td>
</tr>
<tr>
<td>520</td>
<td>2</td>
</tr>
<tr>
<td>1077</td>
<td>3</td>
</tr>
<tr>
<td>1564</td>
<td>4</td>
</tr>
<tr>
<td>497</td>
<td>5</td>
</tr>
<tr>
<td>480</td>
<td>6</td>
</tr>
<tr>
<td>500</td>
<td>7</td>
</tr>
<tr>
<td>493</td>
<td>8</td>
</tr>
<tr>
<td>427</td>
<td>9</td>
</tr>
<tr>
<td>484</td>
<td>10</td>
</tr>
<tr>
<td>483A</td>
<td>11A</td>
</tr>
<tr>
<td>483B</td>
<td>11B</td>
</tr>
</tbody>
</table>

LSC AZ 285°

116° Zone of No Fragments

SRM1

CORE

0 200 ft
RANGE

Reconstruction Based on Recovered SRM Fragments

INSIDE LOOKING OUT

FORWARD
FC CLOSURE
Segment VI
 Segment V
 Segment IV
 Segment III
 Segment II
 Segment I

285° AZ
LSC 0° TDC
FRAGMENT LOCI GENERATED FROM THE RSD OF TITAN 34D-9 SRM1

Segment III

108\(^\circ\) Zone of No Fragments
110B PLUS 110C-SEG IV AND 108/110-SRM2, SEG IV

Segment IV

128\(^\circ\) Zone of No Fragments
110B-SEG III AND 108/110-SRM2, SEG IV

Segment IV-SEG V

110A, D, F PLUS 1110E-SEG V
OBSERVED STS-51L FRAGMENT VELOCITIES (1)

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
Cumulative Probability

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
Fragmnet Velocity, 1ps.

(1) Parker, L., Final Report of the STS 51-L Explosion Working Group (Draft), Section IV, "Solid Rocket Motor Fragmentation Analysis"
IMPLICATIONS OF THE PHYSICAL EVIDENCE STUDY

- TO BE CREDIBLE, ANY MODEL MUST PREDICT THE MAGNITUDE OF THE OBSERVED FRAGMENT ATTRIBUTES WITH A REASONABLE DEGREE OF ACCURACY. THESE ATTRIBUTES INCLUDE:
  - AZIMUTH OF 34D-9 FRAGMENTS
  - VELOCITIES AND VELOCITY DISTRIBUTIONS OF 34D-9 AND 51L FRAGMENTS
  - ROTATION RATES OF 34D-9 AND 51L FRAGMENTS
  - RANDOM FAILURE CASES MUST SHOW A VELOCITY DEPENDENCE WITH LONGITUDINAL POSITION SIMILAR TO THAT OBSERVED IN THE 34D-9 EVENT

- FAILURE TO PREDICT THE SPECTRUM OF FRAGMENT ATTRIBUTES RELIABLY CONSTITUTES A REQUIREMENT TO REVIEW THE ANALYTICAL METHODS AND TO MAKE APPROPRIATE CHANGES UNTIL PREDICTION AND OBSERVATION COME INTO AGREEMENT.

- SINCE THE 34D-9 AND STS-51L EVENTS OCCURRED AT THE EXTREMES OF THE MET RANGE, A SIMILITUDE ARGUMENT MUST BE MADE TO DEVELOP A DATA BASE. THERE IS NO DIRECT OBSERVATIONAL EVIDENCE OF AN RSD ACTION ON A STS-SRM AT 10 SECONDS MET.
REQUIRED MODEL ATTRIBUTES

- The PISCES code version available accepts models in 2D translational symmetry and 2D axisymmetry. To use this code, it must be shown that the effects of the events of interest can be accurately modeled in two dimensions.

- Factors in this assessment included:
  - Wave transit time required to communicate information occurring in adjacent SRM segments
  - Segment to segment flow effects

- It was concluded that a 2D model was adequate to model an RSD action, but there was a need to account for longitudinal flow effects in random SRM failure cases.

- Relative movement of all segment masses must be tracked throughout the event.
  - Couple gas-dynamics to movement of grain and casing.
  - Solve material constitutive equations, momentum equations and energy equations for all model constituents simultaneously.

- The model must produce results consistent with the physical evidence obtained from the 34D-9 and STS-51L events.
MODEL DEVELOPMENT

• FOUR SEPARATE MODELS WERE DEVELOPED TO EVALUATE THE VARIOUS MET DEPENDENT SRM FRAGMENTATION MODES. THESE MODELS WERE:

  • EARLY MET 2D TRANSLATIONAL SYMMETRY COUPLED EULER-LAGRANGIAN MODEL FOR BOTH THE STS AND 34D (34D USED IN MODEL VERIFICATION).

  • A LATE MET 2D TRANSLATIONAL SYMMETRY COUPLED EULER-LAGRANGIAN MODEL WITH A PROVISION FOR Z-FLOW INTRODUCTION.

  • A COUPLED EULER-LAGRANGIAN MODEL TO DETERMINE THE SRM LONGITUDINAL PRESSURE DISTRIBUTION EXTANT DURING RANDOM FAILURE.

  • A FAST RUNNING POST PROCESSOR MODEL WHICH WAS USED TO INVESTIGATE PARAMETER SENSITIVITY AND TO DEVELOP A Viable FRAGMENT ENVIRONMENT DATA BASE.

• ALL OF THESE MODELS WERE USED IN THE DEVELOPMENT OF THE FRAGMENT ENVIRONMENTS PRESENTED IN THE SHUTTLE DATA BOOK (NSTS-08116).

• EACH OF THESE MODELS WILL BE DISCUSSED IN TURN.
EARLY MET COUPLED EULER-LAGRANGIAN MODEL DESCRIPTION

● A DETAILED COUPLED EULER-LAGRANGIAN 2D TRANSLATIONAL SYMMETRY MODEL WAS DEVELOPED TO DETERMINE EARLY MET HOT GAS AND SRM COMPONENT INTERACTIONS. KEY FEATURES OF THIS MODEL ARE SHOWN IN THE ADJACENT VUGRAPHS.

● EQUILIBRIUM STORED STRAIN ENERGY WAS ESTABLISHED BY RUNNING A JOINED MODEL UNTIL PROBLEM KINETIC ENERGY WENT TO ZERO.


● A LIP WAS INTRODUCED INTO THE HIGH VELOCITY GAS ISSUING FROM CRACKS IN THE GRAIN. THE PURPOSE OF THIS LIP WAS TO PROVIDE A MEANS TO PRESSURIZE THE CASE-GRAIN CAVITY.

● TYPICAL FLOW FIELD RESPONSES ARE SHOWN AS A FUNCTION OF TIME IN THE ADJACENT VUGRAPH. THE LIP IS A COMPUTATIONAL CONVENIENCE WHICH HAS CAUSED CONSIDERABLE CONFUSION. IT WILL BE EXPANDED UPON SHORTLY.
### SUMMARY OF SRM FRAGMENT MODEL FEATURES

<table>
<thead>
<tr>
<th>Model Rationale</th>
<th>Model Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Grain (PBAN) Plays a Major Role in Fragment Velocity Behavior at Early MET</td>
<td>• Fully Dynamic</td>
</tr>
<tr>
<td>• Properties of PBAN Under Dynamic Loading Are Not Well Known. (1)</td>
<td>• Constitutive Equations, Energy Equations and Equations of Motion Solved Simultaneously Using Explicit–Finite–Difference Techniques</td>
</tr>
<tr>
<td>• It was Postulated that the Only Reliable Way to Model SRM Fragmentation was to Predict the Behavior of the 34D-9 Event in Detail, Make a Macro Calibration of the Material Properties and Methods Used and Devise a Method of Generalizing the Observed Fragment Velocity Distribution.</td>
<td>• Gas Dynamics Coupled to the Casing and Grain Motions</td>
</tr>
<tr>
<td>• SRM Failure Occurred in a Time Domain Only a Few Percent of the First Mode of the 34D-SRM. It was reasoned that Wave Interactions Were Important and a Hydrocode Should Be Used to Exercise the Model.</td>
<td>• 2-D Translational Symmetry Used for Component Motions</td>
</tr>
<tr>
<td>• Also Because of Wave Transit Time Considerations, It Was Assumed that Translational Symmetry Arguments Were Adequate for the Component Motion Analyses.</td>
<td>• No Influence on Segment of Interest by Adjacent Segments is Assumed</td>
</tr>
<tr>
<td></td>
<td>• 2-D Axisymmetry Used for Gas Dynamics</td>
</tr>
<tr>
<td></td>
<td>• Longitudinal Chamber Flow Must be Considered in Random Failure Case</td>
</tr>
<tr>
<td></td>
<td>• Non-Radial Trajectory</td>
</tr>
<tr>
<td></td>
<td>• Casing Fragment's Trajectory Predicted Based on Assumed Range of Casing Fragmentation Times</td>
</tr>
<tr>
<td></td>
<td>• Rotation Rates Predicted</td>
</tr>
<tr>
<td></td>
<td>• Fragment Velocity Distribution Predicted</td>
</tr>
<tr>
<td></td>
<td>• Predicted Results Were Matched to 34D-9 Results by Assumption of an Effective-Pressure Reduction Factor (Kp)</td>
</tr>
<tr>
<td></td>
<td>• A Similitude Argument was Used for STS Velocity Distribution Predictions</td>
</tr>
</tbody>
</table>

---

34D-9 MODEL INITIAL GEOMETRY SHOWING GRAIN SLIDELINE LOCATIONS

SLIDELINE BETWEEN GRAIN SUBGRIDS (TYP. 5 PLACES)

SLIDELINE BETWEEN CASING AND GRAIN

0°  45°  90°  135°  180°  225°  270°  315°
# SUMMARY OF MATERIAL CONSTITUTIVE PROPERTIES AND MODELS USED IN THE SHUTTLE DATA BOOK SRM FRAGMENT VELOCITY MODEL

<table>
<thead>
<tr>
<th>Material</th>
<th>Equation of State</th>
<th>Yield Model</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Bulk Modulus KBAR</td>
<td>Reference Density gm/cc</td>
</tr>
<tr>
<td>Casing Steel, D6A Grain, PBAN</td>
<td>Poly.</td>
<td>1670</td>
<td>7.86</td>
</tr>
<tr>
<td>Grain Reaction Gas</td>
<td>$\gamma,1.142$</td>
<td>-</td>
<td>0.00571 (c)</td>
</tr>
</tbody>
</table>

(a) The Thiokol Prony Model Could Have Been Mechanized Within the Pisces Code to Model Visco-Elastic Effects. It was Felt that this Refinement was not Justified Because of the Large Uncertainty in the Behavior of PBAN Under Destructive Disassembly Loading.

(b) The Rubber Insulator is Treated as Having the Same Physical Response as the Grain. The PBAN is Adjusted from 1.76 GM/CC to Account for the Presence of the Insulation.

(c) Varies with Burn Time. See FSC-ESD-217-88-426, Table 5 for Details.

EARLY MET COUPLED EULER-LAGRANGIAN MODEL DESCRIPTION (CONT’D)

• A SERIES OF CONTOUR PLOTS OF THE PRESSURE WITHIN THE CAVITY WAS PREPARED.

• THE AVERAGE PRESSURE ACTING ON THE CASING WAS DETERMINED FROM THESE CONTOUR PLOTS AS A FUNCTION OF TIME.

• THE GEOMETRIC RESPONSE OF THE VARIOUS CONTINUA WERE RECORDED.

• THIS DETAILED MODEL WAS USED TO PREDICT THE RESPONSE OF BOTH THE 34D-9-SRM AND THE STS-SRM AT 10 SECONDS MET. ADDITIONAL COUPLED CALCULATIONS WERE PERFORMED AT LATER MET.
DEVELOPING FLOW FIELD IN THE GRAIN - CASING CAVITY
AT VARIOUS TIMES AFTER A 34-D SRM CASING FAILURE AT 10sec MET

TIME = 1.9 msec
CONTOURS = 2.0 BARS

TIME = 3.0 msec
CONTOURS = 2.0 BARS

TIME = 4.0 msec
CONTOURS = 1.0 BAR

TIME = 4.8 msec
CONTOURS = 1.0 BAR
CAVITY PRESSURIZATION

- THE ADJACENT VUGRAPH SHOWS THE GENERAL BEHAVIOR OF AN SRM AS IT UNDERGOES DYNAMIC DISASSEMBLY. THE SEQUENCE OF EVENTS POSTULATED FOR THE MODEL WAS AS FOLLOWS:

- THE STORED STRAIN ENERGY IN THE CASING CAUSES THE CIRCUMFERENCE OF THE CASING TO CONTRACT RELATIVE TO THE CIRCUMFERENCE OF THE GRAIN. THIS INITIATES A DEBONDING ACTION.

- THE INNER AND OUTER DIAMETERS OF THE GRAIN BEGIN TO EXPAND WHEN THE CASING IS CUT.

- LARGE AMOUNTS OF THE GRAIN EXCEED THE FAILURE STRAIN RELATIVELY QUICKLY IN THE REGION 30° ON EITHER SIDE OF THE LSC.

- CRACKS DEVELOP IN THIS REGION OF HIGH STRAIN. THESE CRACKS MAY BE CONCEPTUALIZED AS POROSITY DISTRIBUTED OVER THE REGION OF HIGH STRAINS. THE ADJACENT VUGRAPH SHOWS HOW SUCH A PATTERN MIGHT DEVELOP.

- GAS FLOWS THRU THIS POROSITY FROM THE CHAMBER TOWARD THE ATMOSPHERE.
EARLY-MET MODEL FORMULATION POSTULATING CASE SEPARATION, CAVITY DEVELOPMENT, GRAIN FRAGMENTATION AND CASING FRAGMENTATION

Release of Strain Energy Stored in Casing Causes a Shortening of Casing Circumference. High Tangential and Lower Radial Casing Velocity Relative to Grain Debonds Case from Grain. This Geometry Represents Zero Time for all Subsequent Calculations.

Cracks Initiate in Grain on Inner Diameter and Grain Begins to Fragment. Flow Passages Open Between Chamber and Cavity. Casing Begins to Accelerate Away from Grain.

RELATIVE MOTION OF CASING AND GRAIN SHOWING CONNECTED Voids DEVELOPING IN HIGH STRAIN AREAS

 Shortly After LSC Initiation, Casing Debonds and Edge Retracts. Grain ID Begins to Grow and Areas of Plastic Strain Develop.

 As Casing Retraction Continues, Chamber Bore Begins to Reach Failure Strain. Grain OD Grows and Areas of High Plastic Strain Propagate. Micro-Cracks Develop in High Strain Regions.

 As Process Continues In Time, Micro Cracks Coalesce Into Connected Voids. These Voids Form Flow Channels Which Allow Venting of Chamber Gas to Atmosphere. Casing Blocks Flow and a Grain-Casing Cavity Forms. Casing Edge (Lip) Passes Over Crack. This Provides a Mechanism for Rapid Cavity Pressurization.
CAVITY PRESSURIZATION (CONT'D)


- IN REALITY, THE CASING EDGE WILL PASS OVER A NUMBER OF SMALL FLOW CHANNELS WHICH HAVE BEEN FORMED BY CONNECTING THE POROSITY INTRODUCED INTO THE GRAIN AT LOCATIONS WHERE THE PBAN EXCEEDS ITS LOCAL STRAIN TO FAILURE.

- LUMPING THE DISTRIBUTED POROSITY IN THE PBAN FRACTURED ZONE INTO A SINGLE CHANNEL IS CONSERVATIVE BECAUSE IT NEGLectS THE ASPECT RATIO LOSS CONSIDERATIONS IN THE SERIAL SUPersonic NOzzLES CREATED WITHIN THE FRACTURED ZONE.


- FROM THE STANDPOINT OF THE EQUATIONS OF MOTION, IT DOES NOT MATTER THAT THE POROSITY IS LUMPED. ONLY SO MUCH FLOW AREA CAN OCCUR FROM GRAIN MOTION IN A GIVEN PERIOD OF TIME. (F = MA)
LATE MET MODELS

• THE PHYSICAL EVIDENCE OF THE 51L-EVENT IMPLIED THAT THERE IS A GRAIN THICKNESS AT WHICH DEBONDING WILL NOT OCCUR.

• IT WAS ESTIMATED BY OTHERS THAT THIS TRANSITION WOULD OCCUR AT APPROXIMATELY 105 SECONDS MET WHEN THE GRAIN WAS APPROXIMATELY SIX INCHES THICK.

• A LATE MET MODEL WAS DEVELOPED TO HANDLE THE SPECIAL CASE OF NO FUEL-CASING DEBONDING.
LATE MET MODELS (CONT’D)

• THE LATE MET MODEL IS A FULLY COUPLED EULERIAN-LAGRANGIAN MODEL WHICH SOLVES THE SRM MATERIAL CONSTITUTIVE EQUATIONS, THE EQUATIONS OF MOTION, AND THE GAS DYNAMICS EQUATIONS SIMULTANEOUSLY.

• NO CAVITY IS FORMED IN THIS MODEL.

• GRAIN AND CASING DO NOT DEBOND.

• 2D MOTION OF GRAIN AND CASING ARE ASSUMED; HOWEVER, 3D-FLOW IS CONSIDERED FOR RANDOM FAILURE CASES.

• SINCE THE AFT CYLINDER OF ONE OF THE SEGMENTS OF INTEREST HAD NO FUEL REMAINING AT 110 SECONDS MET, IT WAS NECESSARY TO RUN TWO CASES WITH THIS MODEL (2.7 INCHES OF GRAIN REMAINING AND NO GRAIN REMAINING.)

• THE LATE TIME RSD AND RANDOM FAILURE MODELS ARE SIMILAR. EXAMPLES OF THE MODEL AND ITS RESULTS WILL BE PRESENTED SUBSEQUENTLY.
RANDOM FAILURE MODELS

• THE RANDOM FAILURE EVENTS REQUIRED DETAILED MODELING OF THE LONGITUDINAL HOT GAS FLOW AS WELL AS OF THE RADIAL HOT GAS FLOW.

• REDUCTION OF THE 34D-9 SRM-2 DATA SHOWED THAT THE OBSERVED FRAGMENT VELOCITIES HAD A PRONOUNCED LONGITUDINAL POSITION DEPENDENCE. THE TRENDS OF THIS DEPENDENCE IS SHOWN IN THE ADJACENT VUGRAPH.

• THE SRM-2 FAILURE OCCURRED IN SEGMENT 1 AND A CRACK PROPAGATED UPWARD THRU SEGMENT 4. SEGMENTS 5 AND 6 DID NOT FRAGMENT, BUT FLEW AS A SINGLE COMPONENT TO IMPACT ON AN ADJACENT PAD.

• THE NET EFFECT OF THIS INITIAL LONGITUDINAL POSITION DEPENDENCY DELAY IN FRAGMENTATION INITIATION WAS TO ALLOW THE CHAMBER PRESSURE TO FALL BELOW THE LEVEL REQUIRED TO FRAGMENT THE GRAIN AND CASING OF SEGMENTS 5 AND 6.
CORRELATION OF PREDICTED AND OBSERVED RESULTS FROM THE 34D-9 SRM RANDOM FAILURE

Note: Subsequent Film Evidence Confirmed that the Effective Crack Propagation Rate was 320 m/s
RANDOM FAILURE MODELS (CONT’D)

- THE EFFECT OF LONGITUDINAL FLOW ON THE ENERGY STORED IN ANY SRM SEGMENT WAS ASSESSED AS A FUNCTION OF TIME WITH AN AXISYMMETRICAL FLOW MODEL WHICH ALLOWED SEGMENT LEAKAGE AREA TO VARY AS A FUNCTION OF TIME. THIS EFFECT IS SHOWN IN THE ADJACENT VUGRAPH.

- A FULLY-COUPLED Z-FLOW MODEL WAS USED TO ASSESS THE FRAGMENT VELOCITIES GENERATED BY LATE MET RANDOM FAILURE. THE RESULTANT FLOW FIELD AND PREDICTED FRAGMENT VELOCITIES ARE SHOWN IN THE ADJACENT VUGRAPHS.

- IT WAS FOUND THAT THE FRAGMENT VELOCITIES RESULTING FROM RANDOM SRM CASING FAILURE WERE 0.30 TO 1.07 TIMES THOSE OF THE EQUIVALENT SEGMENT FRAGMENT VELOCITIES DEVELOPED IN RSD INITIATED EVENTS.
TIME-HISTORY OF THE PRESSURE AT FIVE LONGITUDINAL DISTANCES FROM THE 34D-SRM HEAD AFTER RANDOM FAILURE IN SEGMENT 1 AT 10 SECONDS MET FOR TWO CRACK PROPAGATION RATES

CRACK PROPAGATION RATE = 534 m/s

CRACK PROPAGATION RATE = 320 m/s
FLOW FIELD DEVELOPING AROUND A RANDOMLY FAILED STS CENTER-SEGMENT FORWARD-CYLINDER WITH FRAGMENTATION OCCURRING 5 msec AFTER INITIAL CASING FAILURE
STS-SRM CASING GEOMETRY FOR FOUR ASSUMED FRAGMENTATION TIMES
20 MSEC AFTER A RANDOM CASING FAILURE

TIME-HISTORY OF FRAGMENT VELOCITIES RESULTING FROM THE RANDOM FAILURE
OF A STS-SRM FOR FOUR ASSUMED FRAGMENTATION TIMES AT 110 SECONDS MET
(SQUARED NUMBERS REFER TO FRAGMENTS SHOWN IN ABOVE FIGURE)
POST-PROCESSOR MODEL

THE POST-PROCESSOR MODEL WAS DEVELOPED TO PROVIDE A MEANS TO PERFORM THE SENSITIVITY STUDY NECESSARY TO UNDERSTAND THE OBSERVED 34D-9 FRAGMENT VELOCITY DISTRIBUTION.

JAFFE (JPL) NOTED THAT THE RESULTS FROM THE COUPLED EULER RUNS COULD BE NORMALIZED ACROSS BOOSTERS AND ACROSS MET. THIS ALLOWED A MECHANISM FOR PRODUCING A FAST RUNNING "POST PROCESSOR" (STRESS BOUNDARY) MODEL.

THE NORMALIZED CURVES USED AS A FORCING FUNCTION FOR THE POST PROCESSOR MODEL ARE SHOWN IN THE ADJACENT VUGRAPH.

THE RESULTS OBTAINED FROM THE POST PROCESSOR MODEL WERE COMPARED TO THE 34D-9 DATA BASE AT 10 SECONDS MET.

NO VELOCITY IN THE DATA BASE EXCEEDED THAT PREDICTED BY THE COUPLED EULER-LAGRANGIAN CALCULATIONS-130 M/S FOR A FRAGMENT WITH PIECE 1564 GEOMETRY AND SRM FRAGMENTATION TIMES OF 5 TO 12 MSEC AFTER INITIAL GAS FLOW THRU THE GRAIN.
DIMENSIONLESS CHAMBER AND CAVITY Pressures as a Function of Time After Linear Shaped Charge Initiation

Hydrocode Predicted Cavity to Chamber Pressure Ratio

Titan

STS

Cavity

Time (msec)
POST-PROCESSOR MODEL (CONT'D)

• A NUMBER OF FRAGMENTS HAD LOWER VELOCITIES THAN THOSE PREDICTED FOR THE FAST, CUTLINE FRAGMENTS.

• A FACTOR ($K_p$) WAS INTRODUCED TO ACCOUNT FOR THE DISTRIBUTION OF FRAGMENT VELOCITIES SEEN IN THE 34D-9 EVENT.

• THIS FACTOR WAS ALWAYS LESS THAN 1.0; i.e., $K_p$ ALWAYS HAD THE EFFECT OF REDUCING THE PREDICTED VELOCITY TO PROVIDE FOR THE OBSERVED VELOCITY DISTRIBUTION.

• A SERIES OF 250 RUNS WAS MADE TO PROVIDE A STATISTICAL BASIS FOR THE FRAGMENT VELOCITY AND AZIMUTH ENVIRONMENT CREATED BY A VARIETY OF RANGE DESTRUCT AND RANDOM STS-SRM FAILURES OCCURRING BETWEEN 0 TO 110 SECONDS MET.

• THE ONLY VARIABLES IN THIS SERIES WERE THE CAVITY PRESSURE REDUCTION FACTOR ($K_p$) AND THE SRM CASING FRAGMENTATION TIME. (TIME OF FIRST GAS VENTING THRU THE GRAIN IS TIME ZERO.) TYPICAL RESULTS ARE PRESENTED IN THE ADJACENT VUGRAPHS.
34D-SRM CASING GEOMETRY FOR FOUR ASSUMED FRAGMENTATION TIMES
20 MSEC AFTER A RANGE DESTRUCT ACTION AT 10 SECONDS MET

TIME-HISTORY OF FRAGMENT VELOCITIES RESULTING FROM THE
RANGE DESTRUCTION OF A 34D-SRM FOR FOUR ASSUMED
FRAGMENTATION TIMES AT 10 SECONDS MET (SQUARED
NUMBERS REFER TO FRAGMENTS SHOWN IN ABOVE PANEL)
EFFECT OF FRAGMENTATION TIME ON THE VELOCITY AND AZIMUTH OF THE HIGHEST VELOCITY 34D-SRM FRAGMENTS (Number 4, FAST OCTANTS), SHOWN IN ADJACENT VUGRAPH
POST PROCESSOR MODEL (CONT'D)

- POST PROCESSOR MODEL RUNS DID NOT COUPLE THE GAS DYNAMICS TO THE MOVEMENT OF THE SRM MATERIALS.

- THE NORMALIZED PRESSURE-TIME-HISTORY WAS APPLIED TO THE RELEVANT AREAS OF THE VARIOUS COMPONENTS AS A STRESS BOUNDARY AND THE EQUATIONS FOR MOTION WERE SOLVED IN LAGRANGIAN COORDINATES.

- CRITICISMS OF THE MANNER IN WHICH THE VARIOUS SRM MASSES WERE ALLOWED FREEDOM TO MOVE (INDUCED SLIDE LINES) HAVE BEEN MADE.

- THESE CRITICISMS ARE BASED ON THE NOTION THAT MATERIAL STRENGTH PLAYS A LARGER ROLE THAN MATERIAL INERTIA IN EVENTS WHICH OCCUR IN A 20 TO 30 MSEC TIME FRAME.

- THE RELATIVE IMPORTANCE OF THESE FACTORS WILL BE DISCUSSED SUBSEQUENTLY.
MODEL DEVELOPMENT CONCLUSION

• THE UTILITY OF THE MODEL IS BEST DETERMINED BY ASSESSING HOW WELL ITS PREDICTIONS MET THE PROGRAM OBJECTIVES.

THIS ASSESSMENT WAS MADE BY COMPARING THE MODEL PREDICTIONS TO THE RESULTS OBSERVED FOR THE 34D-9 AND STS-51L EVENTS.

AS CAN BE SEEN FROM THE ADJACENT VUGRAPHS, GOOD AGREEMENT BETWEEN PREDICTIONS AND OBSERVATIONS WAS OBTAINED FOR FRAGMENT:

• VELOCITY
• VELOCITY DISTRIBUTIONS
• AZIMUTHS
• ROTATION RATES

• BASED ON THIS AGREEMENT WITH THE ENTIRE DATA BASE, THE MODEL WAS USED TO PREDICT THE PROBABLE FRAGMENT ENVIRONMENTS WHICH WOULD OCCUR IN THE EVENT OF STS-SRM RSD OR RANDOM FAILURE AT 10, 74, 84, AND 110 SECONDS MET.

• THE RESULTS OF THESE PREDICTIONS ARE THE BASIS OF THE FRAGMENT ENVIRONMENTS PRESENTED IN THE SHUTTLE DATA BOOK (NSTS-08116).
## COMPARISON OF THE OBSERVED AND PREDICTED FRAGMENT VELOCITY AND AZIMUTH RESULTING FROM THE RANGE DESTRUCT OF SRM-1 IN THE 34D-9 EVENT

<table>
<thead>
<tr>
<th>Observations Based On T34D-9 Range Data</th>
<th>Predictions Based On Hydrocode Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>Piece</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>497</td>
</tr>
<tr>
<td>3</td>
<td>493</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>427</td>
</tr>
<tr>
<td>5</td>
<td>1564</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Kp** = 0.2</th>
<th>Kp** = 0.4</th>
<th>Kp** = 0.2</th>
<th>Kp** = 0.4</th>
<th>Kp** = 0.2</th>
<th>Kp** = 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>520</td>
<td>248</td>
<td>-86</td>
<td>56</td>
<td>-86</td>
<td>12</td>
<td>38</td>
<td>-86</td>
<td>12</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>538</td>
<td>194</td>
<td>-56</td>
<td>39</td>
<td>-91</td>
<td>10</td>
<td>27</td>
<td>-91</td>
<td>10</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>480</td>
<td>162</td>
<td>71</td>
<td>30</td>
<td>91</td>
<td>10</td>
<td>27</td>
<td>91</td>
<td>10</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>484</td>
<td>251</td>
<td>128</td>
<td>53</td>
<td>109</td>
<td>18</td>
<td>45</td>
<td>109</td>
<td>18</td>
<td>59</td>
</tr>
<tr>
<td>4/6</td>
<td>1077</td>
<td>133</td>
<td>-63</td>
<td>27</td>
<td>-91</td>
<td>10</td>
<td>29</td>
<td>-91</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>5/6</td>
<td>483</td>
<td>206</td>
<td>117</td>
<td>43</td>
<td>106</td>
<td>18</td>
<td>22</td>
<td>106</td>
<td>18</td>
<td>64</td>
</tr>
</tbody>
</table>

*Initial Casing Failure at 0 Degree  **Arbitrary Cavity-Pressure Reduction Factor Used to Match Observed Results(7)  †Fragmentation Time.
COMPARISON OF PREDICTED AND MEASURED VELOCITIES FOR AN STS-SRM AT 110 SEC MET

![Graph showing cumulative probability against fragment velocity with curves for Parker Analysis (Weibull Fit) and Model.](image)
# SUMMARY OF THE PREDICTED AND OBSERVED FRAGMENTATION RESPONSE OF SEVERAL VEHICLE ELEMENTS TO A NUMBER OF INTERNAL PRESSURE ENVIRONMENTS

<table>
<thead>
<tr>
<th>Booster / Event</th>
<th>Vessel Pressure at Time of Initial Failure</th>
<th>Failure MET</th>
<th>Fragmentation Time ( \text{(sec)} )</th>
<th>Predicted Range of Fragment Velocities ( \text{(m/s)} )</th>
<th>Observed Range of Fragment Velocities</th>
<th>Predicted Range of Fragment Rotation Rates ( \text{(Hz)} )</th>
<th>Observed Range of Fragment Rotation Rates ( \text{(Hz)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>34D-9 Range Destruct</td>
<td>54.5</td>
<td>10</td>
<td>0-20</td>
<td>17-104</td>
<td>15-106 ( \text{c) } )</td>
<td>8-12</td>
<td>5-12</td>
</tr>
<tr>
<td>34D-9 Random Failure</td>
<td>54.5</td>
<td>10</td>
<td>0-20</td>
<td>15-111</td>
<td>15-114 ( \text{c) } )</td>
<td>8-12</td>
<td>5-12</td>
</tr>
<tr>
<td>STS Range Destruct</td>
<td>60.</td>
<td>10</td>
<td>0-20</td>
<td>2-108</td>
<td>-</td>
<td>1-12</td>
<td>-</td>
</tr>
<tr>
<td>STS Random Failure</td>
<td>60.</td>
<td>10</td>
<td>0-20</td>
<td>2-115</td>
<td>-</td>
<td>1-12</td>
<td>-</td>
</tr>
<tr>
<td>STS Range Destruct</td>
<td>41.4</td>
<td>84</td>
<td>0-20</td>
<td>30-104</td>
<td>-</td>
<td>1-11</td>
<td>-</td>
</tr>
<tr>
<td>STS Random Failure</td>
<td>41.4</td>
<td>84</td>
<td>0-20</td>
<td>53-123</td>
<td>-</td>
<td>1-12</td>
<td>-</td>
</tr>
<tr>
<td>STS-51L Range Destruct (Fwd. Cyl.)</td>
<td>31.0</td>
<td>110</td>
<td>0-20</td>
<td>6-162</td>
<td>15-198</td>
<td>0-11</td>
<td>3-17</td>
</tr>
<tr>
<td>STS-51L Range Destruct (Alt. Cyl.)</td>
<td>31.0</td>
<td>110</td>
<td>0-20</td>
<td>19.8-226.</td>
<td>15-198</td>
<td>1-19</td>
<td>3-17</td>
</tr>
<tr>
<td>STS Random Failure (Fwd. Cyl.)</td>
<td>31.</td>
<td>110</td>
<td>0-20</td>
<td>3.169</td>
<td>-</td>
<td>0-12</td>
<td>-</td>
</tr>
</tbody>
</table>

\( \text{c) } \) Time after initial grain fragmentation at which casing fragments are generated. The latest time at which shell stresses can be supported by casing-materials' strength.

\( \text{d) } \) A 320 m/s propagation rate is used to communicate the crack from segment to segment.

\( \text{e) } \) Based on analyses of range data performed by Jaffe\(^3\) using a six degree of freedom code.

\( \text{f) } \) Instantaneous fragmentation is assumed in the randomly failed segment followed by subsequent segment casing failure up to 20 msec after the arrival of a propagating (320 m/s) crack at the relevant segment boundary.

\( \text{g) } \) Ranges vary from early-fragmentation-large-fragments to late-fragmentation time-small fragments adjacent to the initial casing-crack free-surface.

\( \text{h) } \) Note that all random failure generated fragment velocity ranges are for the fragmented cylinder. The cylinders adjacent to this cylinder will have serially decreasing maximum fragment velocities. This decrease may be more than a factor of two when the randomly failed cylinder is at a stack extreme. At low crack propagation rates the extreme cylinder may not fragment.
MODEL REVIEW AND BOUNDARY ASSUMPTION VERIFICATIONS

- SANITY CHECKS -

● IT IS ALWAYS USEFUL TO STEP BACK AND ASK IF WHAT IS BEING MODELED MAKES PHYSICAL SENSE.

● SEVERAL INVESTIGATORS HAVE SUGGESTED THAT THE TOTAL ENERGY STORED IN THE STS-SRM AT 10 SECONDS MET IS SIGNIFICANTLY HIGHER THAN THAT STORED IN THE 34D-SRM. THIS ARGUMENT IS VALID; HOWEVER, AS SHOWN IN THE ADJACENT VUGRAPH, IT MISSES THE POINT.

● THE PISCES CODE IS WELL KNOWN AND WELL CALIBRATED. THIS NOTWITHSTANDING, HYDROCODE MODELING HAS A NUMBER OF PITFALLS AND IT IS RELATIVELY EASY TO GET TRAPPED IN THEM.

● STEVE HANCOCK, THE PRINCIPAL AUTHOR OF THE PISCES CODE, WAS RETAINED TO REVIEW THE PREVIOUSLY PRESENTED WORK.

● MR. HANCOCK PERFORMED A NUMBER OF ANALYSES TO PROVIDE FIRST ORDER PREDICTIONS OF THE RELATIVE MOTIONS OF SRM CASING AND GRAIN FRAGMENTS ASSUMING RADIAL TRAJECTORIES FOR BOTH. THE ANALYTICAL MODELS USED TO GENERATE THESE RESULTS ARE SHOWN IN THE ADJACENT VUGRAPHS.

● THE PURPOSE OF THESE ANALYSES WAS TO BOUND THE RANGE OF VELOCITIES WHICH COULD BE PRODUCED BY THE AVAILABLE ENERGY AND THE PROBABLE PARTITION OF THAT ENERGY.
TITAN 34D AND STS\(^{(1)}\) SIMILITUDE

- **TITAN AND STS CHAMBER GAS ENERGY RATIO PER UNIT LENGTH AT 10 SEC MET**

\[
\frac{(PV)_{34D}}{(PV)_{STS}} = \left( \frac{\text{Chamber Pressure}_{34D}}{\text{Chamber Pressure}_{STS}} \right) \left( \frac{(\text{Average Chamber Diameter}_{34D})^2}{(\text{Average Chamber Diameter}_{STS})^2} \right)
\]

\[
\frac{(PV)_{34D}}{(PV)_{STS}} = \left( \frac{793}{843} \right) \left( \frac{(53.4)^2}{(65.6)^2} \right) = 0.62
\]

- **TITAN AND STS CASING, JOINT AND INSULATION MASS RATIO PER UNIT LENGTH**

\[
\frac{\text{Mass}_{34D}}{\text{Mass}_{STS}} = \left( \frac{576}{900} \right) = 0.64
\]

- **FIRST ORDER SIMILITUDE EXPECTATION**

\[
\frac{\text{Velocity}_{34D}}{\text{Velocity}_{STS}} = \left( \frac{\text{Chamber Energy Ratio}}{\text{Mass Ratio}} \right)^{\frac{1}{2}} = \left( \frac{0.62}{0.64} \right)^{\frac{1}{2}} = 0.98
\]

**CONCLUSION:**

One Would Expect the Observed 34D-9 SRM-1 Fragment Environment to be a Good Approximation of an STS Fragment Environment Generated by an RSD at \(~10\) Seconds MET

\(^{(1)}\) STS Parameters from NSWC TR 80-417 (Reference Memorandum J. A. Roach to J. Petes)
### SUMMARY OF UNIT STORED ENERGY AND UNIT MASS FOR THE 34D AND STS SRM AT VARIOUS MET

<table>
<thead>
<tr>
<th>SRM Type</th>
<th>MET</th>
<th>PBAN Grain Mass</th>
<th>Casing + Joint + ½ Insulation Mass</th>
<th>Stored Energy</th>
<th>Ratio of Stored Energy to Grain Mass</th>
<th>Ratio of Stored Energy to Mass</th>
<th>Ratio of Stored Energy to Sum of Masses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sec</td>
<td>kg/ft</td>
<td>kg/ft</td>
<td>eu(1)/ft</td>
<td>eu/kg</td>
<td>eu/kg</td>
<td>eu/kg</td>
</tr>
<tr>
<td>34D</td>
<td>10</td>
<td>3131.</td>
<td>261.</td>
<td>182.</td>
<td>.0581</td>
<td>.697</td>
<td>.0536</td>
</tr>
<tr>
<td>STS</td>
<td>10</td>
<td>4636.</td>
<td>408.</td>
<td>281.</td>
<td>.0606</td>
<td>.689</td>
<td>.0557</td>
</tr>
<tr>
<td>STS</td>
<td>37</td>
<td>3745.</td>
<td>408.</td>
<td>406.</td>
<td>.109</td>
<td>1.00</td>
<td>.0978</td>
</tr>
<tr>
<td>STS</td>
<td>84</td>
<td>1905.</td>
<td>408.</td>
<td>650.</td>
<td>.214</td>
<td>1.59</td>
<td>.281</td>
</tr>
<tr>
<td>STS-FWD-CYL</td>
<td>110</td>
<td>426.</td>
<td>408.</td>
<td>663.</td>
<td>1.56</td>
<td>1.62</td>
<td>.794</td>
</tr>
<tr>
<td>STS-STAR-GR</td>
<td>110</td>
<td>0.0</td>
<td>539.</td>
<td>721.</td>
<td>-</td>
<td>1.34</td>
<td>1.34</td>
</tr>
<tr>
<td>STS-STAR-GR</td>
<td>20</td>
<td>0.0</td>
<td>539.</td>
<td>1408.</td>
<td>-</td>
<td>2.61</td>
<td>2.61</td>
</tr>
</tbody>
</table>

(1) One eu = 10^{12} ergs.

### CONCLUSIONS:

1. The Ratio of Unit Stored Energy to Unit Casing Mass is Greater in a 34D-SRM than it is in an STS-SRM.
2. This is Consistent with the Shuttle Data Book Model Prediction that Fragments Generated by an RSD at 10 SEC MET will be Lower in Velocity for an STS-SRM then for a 34D-SRM.
MODEL REVIEW AND BOUNDARY ASSUMPTION VERIFICATIONS (CONT'D)

- SANITY CHECKS (CONT'D) -

• IN ADDITION, MR. HANCOCK WAS ASKED TO REVIEW THE MODELING ASSUMPTIONS TO MAKE SURE HIS CODE HAD NOT BEEN MISUSED.

AMONG THE PHENOMENA MR. HANCOCK EVALUATED WERE:

• THE EXTENT TO WHICH THE PROBLEM IS TWO-DIMENSIONAL (EFFECTS OF BENDING WAVE SPEED).

• EFFECTS OF THE PRESENCE OF GRAIN ON GAS DYNAMICS. THESE EFFECTS ARE SHOWN ON THE ADJACENT VUGRAPH.

• EFFECT OF FRAGMENT ROTATION ON GRAIN-CASING CAVITY PRESSURE. THIS EFFECT IS SHOWN ON THE ADJACENT VUGRAPH.

• EFFECT OF 3D FLOW ON PRESSURE BETWEEN THE GRAIN AND THE CASING. THIS EFFECT IS ILLUSTRATED AND THE RESULTS ARE SHOWN ON THE ADJACENT VUGRAPHS.

• THE RESULTS OF THIS STUDY ARE SUMMARIZED AND COMPARED TO THE HYDROCODE MODEL PREDICTIONS. THESE RESULTS ARE SHOWN ON THE ADJACENT VUGRAPHS.
MASS AND ENERGY FLOW

Model Geometry

\[ P_1, \rho_1, e_1, \frac{c_1}{c_2}, \quad P_2, \rho_2, e_2, \quad \text{Atmosphere } P_3 \]

Area, \( S_1 \)    Area, \( S_2 \)

Mass Flow from Chamber \( i \) to Chamber \( i + 1 \) (\( i = 1 \) or 2)

\[ \dot{M}_i = (C_{di} S_i + \Delta S_i) \rho_i c_i \sqrt{\frac{2}{\gamma - 1} \left( \frac{\gamma}{\gamma - 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}} \]

\{ Discharge Coefficient \} \quad \{ Geometric Flow Area \} \quad \{ Optional Additional Area (Bypass) \}

\[ r_i = \max \left( \frac{P_{i+1}}{P_i}, \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \right) = \text{Pressure Ratio} \]

Subsonic, Unchoked Flow \quad \text{Choked Flow Limit}

Energy Flow Rate from Chamber \( i \) to Chamber \( i + 1 \)

\[ \dot{E} = \dot{h}_i \dot{M}_i \]

Where:

\[ h_i = e_i + \frac{P_i}{\rho_i} = \text{Specific Enthalpy} \]
FRAGMENT EQUATION OF MOTION

\[ M \frac{dv}{dt} = F \]

\[ F = P_i (2h_i) - P_o (2h_o) + P_s (2h_o - 2h_i) \]

Where:
- \( h \) = Half-Chord Lengths
- \( P_o \) = Outer Pressure
- \( P_s \) = Side Pressure
  \( (= P_i \) in Model at Present)

MASS AND ENERGY BALANCE FOR CHAMBER I

\[ P_i = (\gamma - 1) \frac{E_i}{V_i} \] = Pressure

\[ E_i = \text{Total Internal Energy in Chamber } i \]

\[ V_i = \text{Total Gas Volume in Chamber } i \]

\[ c_i = \sqrt{\frac{\gamma P_i}{\rho_i}} \] = Sound Speed

\[ \rho_i = \frac{M_i}{V_i} \] = Density

\[ M_i = \text{Total Gas Mass} \]

\[ \frac{dE_i}{dt} = - \{ \text{Work Done on Fragments} \} - \{ \text{Energy Flow to Next Chamber} \} + \{ \text{Energy Flow from Chamber i-1 (If Any)} \} \]

\[ \frac{dM_i}{dt} = - \{ \text{Mass Flow to Next Chamber} \} + \{ \text{Mass Flow from Chamber i-1} \} \]
**RIGID BODY 34D-9 MODEL RESULTS USED TO CHECK HYDROCODE RESULTS**

(Pressure = ATMOS., VELOCITY = m/s)

<table>
<thead>
<tr>
<th>Time (msec)</th>
<th>Bonded Casing and Grain Motions</th>
<th>Grain and Casing Motions Resulting from an Assumption that Bypass (3D) Flow Will Equilibrate Chamber and Cavity Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>10.0</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>15.1</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td>18.1</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

(1) Circled Numbers Are Pressures in Atmospheres; Numbers with Vectors Are Velocities in m/s
COMPARISON OF TWO-CHAMBER ANALYTICAL MODEL FRAGMENT VELOCITY FOR THE 34D AND STS-SRM AT MET = 10

<table>
<thead>
<tr>
<th>SRM Type</th>
<th>$E^{(1)}$ Avail. Energy J/m</th>
<th>$M_p$ PBAN Mass kg/m</th>
<th>$M_c$ Case Mass kg/m</th>
<th>$\left( \frac{2E}{M_p + M_c} \right)^{\frac{1}{2}}$ m/s</th>
<th>$\left( \frac{2E}{M_c} \right)^{\frac{1}{2}}$ m/s</th>
<th>$V_c$ Model 0 Hz m/s</th>
<th>$V_c$ Model 7 Hz m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>34D</td>
<td>1.83E7</td>
<td>10.3E3</td>
<td>724</td>
<td>58</td>
<td>224</td>
<td>78</td>
<td>56</td>
</tr>
<tr>
<td>STS</td>
<td>3.19E7</td>
<td>14.3E3</td>
<td>1112</td>
<td>64</td>
<td>239</td>
<td>83</td>
<td>54</td>
</tr>
</tbody>
</table>

(1) Available Energy = Work by Chamber Gas for an Isentropic Expansion to Atmospheric Pressure.

CONCLUSION:
The Predicted Ratio of Fragment Velocities is Consistent With the First Order Similitude Expectation
PARAMETERS USED IN TWO-CHAMBER ANALYTICAL MODEL FOR THE 34D AND STS-SRM AT MET = 10

<table>
<thead>
<tr>
<th>SRM Type</th>
<th>$P_o$</th>
<th>$R_b$ Burn Radius (Vol. Avg.)</th>
<th>$R_c$ Case Radius</th>
<th>$H_c$ Case Thickness</th>
<th>$V_o$ Chamber Volume</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>34D</td>
<td>54.7E5</td>
<td>.678</td>
<td>1.528</td>
<td>9.5</td>
<td>1.44</td>
<td>.308</td>
</tr>
<tr>
<td>STS</td>
<td>58.6E5</td>
<td>0.864</td>
<td>1.83</td>
<td>12.2</td>
<td>2.35</td>
<td>0.314</td>
</tr>
</tbody>
</table>

Common Properties:
- Gas Ratio of Specific Heats, $\gamma = 1.142$
- PBAN Density, $1750$ kg/m$^3$
- Case Density, $7860$ kg/m$^3$

Available Energy $E = f P_o V_o / (\gamma - 1)$

Where:

$$f = 1 - r \left( \frac{\gamma - 1}{\gamma} \right) + (\gamma - 1) r (1 - r \frac{1}{\gamma})$$  

$$r = P_a / P_o$$
TYPICAL SRM CYLINDER GEOMETRY SHOWING 34D AND STS JOINT DETAILS

34D Joint Detail

STS Joint Detail

34D Cylinder Geometry

Grain ID MET = 10

Grain ID MET = 10

Grain ID

Grain ID

Restrictor ID

Restrictor

Notes:

- As Fabricated Dimensions (Inches) Are Shown for Titan 34D-9 Per Written Record of Conference Call Cork, Spitale, and Eck With S. Backlund United Technology Corp 12 Oct 87
- 34D Grain Is One Cylinder Long
- STS Grain Is Two Cylinders Long (~300 Inches) and Essentially Untapered
EFFECT OF FLOW INTO THE CASING-GRAIN CAVITY FROM AN UNSPECIFIED LONGITUDINAL FLOW PATH ON RIGID-BODY-MODEL PREDICTED 34D-9 SRM FRAGMENT VELOCITY

<table>
<thead>
<tr>
<th>Ratio of 3D Bypass Flow Area to Burn Area</th>
<th>Casing Fragment Velocity m/s</th>
<th>Grain Fragment Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>0.001</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>0.01</td>
<td>89</td>
<td>28</td>
</tr>
<tr>
<td>0.02</td>
<td>94</td>
<td>26</td>
</tr>
<tr>
<td>0.04</td>
<td>104</td>
<td>23</td>
</tr>
<tr>
<td>0.08</td>
<td>120</td>
<td>17</td>
</tr>
<tr>
<td>0.16</td>
<td>140</td>
<td>8</td>
</tr>
<tr>
<td>0.20</td>
<td>146</td>
<td>5</td>
</tr>
<tr>
<td>0.40</td>
<td>157</td>
<td>1</td>
</tr>
<tr>
<td>0.50</td>
<td>158</td>
<td>0</td>
</tr>
<tr>
<td>1.00</td>
<td>162</td>
<td>0</td>
</tr>
</tbody>
</table>

CONCLUSION:
A single chamber flow model can be justified if a grain flow channel bypass path with a flow area equal to 40 percent of the grain ID area can be identified. Such a model will produce unrealistically low grain fragment velocities.
NORMALIZED CAVITY AND CHAMBER PRESSURE AS A FUNCTION OF TIME AFTER LSC INITIATION
SUMMARY OF RESULTS OBTAINED FROM THE RIGID BODY MODELS OF STS EVENTS
MODEL BOUNDARY ASSUMPTION VERIFICATION

● A NUMBER OF BOUNDARY ASSUMPTIONS WERE MADE IN THE VARIOUS MODELS USED TO DEVELOP THE SHUTTLE DATA BOOK DATA BASE.

● VARIOUS INVESTIGATORS CALLED MANY OF THESE ASSUMPTIONS INTO QUESTION.

● A TASK WAS INITIATED TO TEST THE ASSUMPTIONS UPON WHICH THE MODELS WERE BASED.

● CENTRAL TO THIS TASK WAS ESTABLISHING THE BEHAVIOR OF THE GRAIN DURING THE PERIOD AFTER THE CASING FAILED AND BEFORE CHAMBER GAS BEGAN TO VENT.

● DETAILED MODELING OF GRAIN AND GRAIN CRACK PROPAGATION WAS UNDERTAKEN TO ANSWER QUESTIONS ABOUT THE RELATIVE IMPORTANCE OF MATERIAL INERTIA AND STRENGTH.

● A COMPLETELY NEW 2D AXISYMMETRICAL COUPLED EULERIAN-LAGRANGIAN MODEL WAS DEVELOPED FOR THIS TASK.
MODEL BOUNDARY ASSUMPTION VERIFICATION (CONT'D)

- THE NEW MODEL HAD THE FOLLOWING FEATURES:

- LOCATIONS WHERE CRACKS COULD INITIATE AND PROPAGATE THRU THE GRAIN.

- CRACK INITIATION WAS BASED ON A LOCAL STRAIN TO FAILURE CRITERION.

- ONLY TEN POTENTIAL CRACK LOCATIONS COULD BE CHOSEN BECAUSE OF CODE ARRAY LIMITATIONS.

- CASING-GRAIN BOND STRENGTH PRIOR TO DEBONDING WAS MODELED.

- GRAIN STRENGTH PRIOR TO GRAIN FRACTURE WAS MODELED.

- EQUILIBRIUM STRESSES WERE ESTABLISHED USING LOW STRAIN RATE MATERIAL PROPERTIES.

- HIGH STRAIN RATE PROPERTIES WERE INTRODUCED AS HIGH RATES DEVELOPED.

- THE MASS OF THE PBAN GAS STORED IN THE CHAMBER AT 10 SEC MET IS FIVE TIMES GREATER THAN THE MASS GENERATED BY BURNING FOR 20 MSEC AT 60 BARS.
MODEL BOUNDARY ASSUMPTION VERIFICATION (CONT’D)

• NO ENHANCED BURNING WAS USED TO INCREASE CHAMBER ENERGY DURING THE ~30 MSEC REQUIRED TO COMPLETE THE BLOW DOWN PROCESS.

• LOCAL TOTAL STRAIN AT THE 10 JOINED LAGRANGIAN SUBGRID LOCATIONS WAS MONITORED AUTOMATICALLY AND THE RUN WAS STOPPED WHEN TOTAL STRAIN EXCEEDED 30 PERCENT.

• DEFECTS WERE INTRODUCED INTO THE GRAIN BY REMOVING THE JOINS BETWEEN ADJACENT SUBGRIDS.

• IF THE DEFECTS COULD COMMUNICATE WITH THE HOT GAS, CHAMBER PRESSURE WAS APPLIED TO THE SEPARATED SURFACES GENERATED BY THE CRACK.

• THE RUN WAS RESTARTED AND THE PROCESS OF MANUALLY REMOVING SUBGRID JOINS WAS CONTINUED UNTIL A CRACK PROPAGATED THRU THE GRAIN.

• CASING AND GRAIN MOTIONS, STRAIN STATES, AND RATES WERE TRACKED UNTIL CHAMBER PRESSURE DISSIPATED.

• THE RESULTS OBTAINED USING THIS PROCESS ARE SHOWN IN THE FOLLOWING VUGRAPHS.
**TIME LINE FOR A STS-SRM SEGMENT RESPONSE TO A RANGE SAFETY DESTRUCT ACTION AT 10 sec MET**

<table>
<thead>
<tr>
<th>Time msec</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Linear shaped charge fired. PBAN cut 12 cm deep at 0°.</td>
</tr>
<tr>
<td>1.2</td>
<td>Debond failure strain reaches 45° and crack initiates on grain external diameter (OD).</td>
</tr>
<tr>
<td>6.2</td>
<td>Debond failure strain reaches 90° and crack initiates on grain OD.</td>
</tr>
<tr>
<td>12.1</td>
<td>Debond failure strain reaches 135° and first crack initiates in grain internal diameter (ID) at GR2/GR3 interface.</td>
</tr>
<tr>
<td>12.4</td>
<td>Crack initiates in grain ID at GR3/GR4 and GR9/GR10 interfaces.</td>
</tr>
<tr>
<td>13.3</td>
<td>Crack initiates at cut-line ID (GR1/GR10 interface).</td>
</tr>
<tr>
<td>14.6</td>
<td>Crack initiates at GR5/GR6 interface and at GR7/GR8 interface by symmetry.</td>
</tr>
<tr>
<td>23.4</td>
<td>First crack has traversed grain at GR3/GR4 interface.</td>
</tr>
<tr>
<td>23.9</td>
<td>Grain cracks thru at GR1/GR10 interface.</td>
</tr>
<tr>
<td>26.1</td>
<td>Grain cracks thru at GR2/GR3 interface.</td>
</tr>
<tr>
<td>26.5</td>
<td>Grain cracks thru at GR9/GR10 interface.</td>
</tr>
</tbody>
</table>
VARIATION OF THE SQUARE ROOT OF THREE TIMES THE SECOND INVARIANT OF THE STRESS DEVIATOR TENSOR

\[ J_2' = \frac{1}{2} (S_{xx}^2 + S_{yy}^2 + 2S_{xy}^2) \]; \text{YIELD} = (3J_2')^{\frac{1}{2}} \approx 48.3 \text{ BARS}

<table>
<thead>
<tr>
<th>Locations where cracks may be propagated</th>
<th>10 Bar Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR1, GR2, GR3, GR4, GR5, GR6, GR7, GR8, GR9, GR10</td>
<td>0.2 msec</td>
</tr>
<tr>
<td>LSC</td>
<td>1.2 msec</td>
</tr>
<tr>
<td>2.0 msec</td>
<td>3.0 msec</td>
</tr>
<tr>
<td>5.0 msec</td>
<td>6.2 msec</td>
</tr>
<tr>
<td>12.1 msec</td>
<td>12.4 msec</td>
</tr>
</tbody>
</table>
VARIATION OF THE SQUARE ROOT OF THREE TIMES THE SECOND IN Variant OF THE STRESS DEVIATOR TENSOR

\[ J_2' = \frac{1}{2} (S_{xx}^2 + S_{yy}^2 + 2S_{xy}^2) \]; \text{YIELD} = (3J_2')^{\frac{1}{2}} \equiv 48.3 \text{ BARS}

<table>
<thead>
<tr>
<th>10 Bar Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>13.3 msec</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>23.9 msec</td>
</tr>
</tbody>
</table>
\[ \dot{\epsilon} = \frac{2}{3}(\dot{\epsilon}_{xx} + \dot{\epsilon}_{yy} + 2\dot{\epsilon}_{xy})^{1/2} \]

VARIATION OF RESULTANT STRAIN RATE (\(\dot{\epsilon}\)) WITH TIME AFTER LSC INITIATION

<table>
<thead>
<tr>
<th>Time (msec)</th>
<th>Contour 1</th>
<th>Contour 2</th>
<th>Contour 3</th>
<th>Contour 4</th>
<th>Contour 5</th>
<th>Contour 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
<tr>
<td>4.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
<tr>
<td>3.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
<tr>
<td>2.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
<tr>
<td>1.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
<tr>
<td>0.0</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
<td>(Diagram)</td>
</tr>
</tbody>
</table>
VARIATION OF RESULTANT STRAIN RATE (\( \dot{\varepsilon} \)) WITH TIME AFTER LSC INITIATION

\[ \dot{\varepsilon} = \frac{2/3}{(\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy} + 2 \dot{\varepsilon}_{xy})^{1/2}} \]

5 Reciprocal Seconds Contours

<table>
<thead>
<tr>
<th>Time (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.3 msec</td>
</tr>
<tr>
<td>14.6 msec</td>
</tr>
<tr>
<td>19.7 msec</td>
</tr>
<tr>
<td>23.9 msec</td>
</tr>
<tr>
<td>26.1 msec</td>
</tr>
<tr>
<td>27.9 msec</td>
</tr>
<tr>
<td>30.1 msec</td>
</tr>
<tr>
<td>33.9 msec</td>
</tr>
<tr>
<td>Grain Total Strain as a Function of Time</td>
</tr>
<tr>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>5 Percent Strain Contours</td>
</tr>
<tr>
<td>0.0 msec</td>
</tr>
<tr>
<td>1.2 msec</td>
</tr>
<tr>
<td>6.2 msec</td>
</tr>
<tr>
<td>12.1 msec</td>
</tr>
<tr>
<td>13.3 msec</td>
</tr>
<tr>
<td>14.6 msec</td>
</tr>
<tr>
<td>23.4 msec</td>
</tr>
</tbody>
</table>
RELATIVE CASING AND GRAIN GEOMETRY AS A FUNCTION OF TIME AFTER THE RSD OF AN STS-SRM AT 10 SEC MET

Vectors Show Casing Edge and Relative Velocity Within Panel Only

1.3 msec
12.1 msec
12.4 msec
13.3 msec
14.6 msec
19.7 msec
23.4 msec
23.9 msec
RELATIVE CASING AND GRAIN GEOMETRY AS A FUNCTION OF TIME
AFTER THE RSD OF AN STS-SRM AT 10 SEC MET

Vectors Show Casing Edge and Relative Velocity Within Panel Only

- 26.1 msec
- 26.5 msec
- 26.9 msec
- 28.1 msec
- 29.1 msec
- 30.8 msec
DEVELOPING FLOW FIELD IN THE GRAIN - CASING CAVITY AT VARIOUS TIMES AFTER A STS-SRM CASING FAILURE AT 10 SECONDS MET

CASING FRAGMENTATION AT 26.9 MSEC

TIME = 26.9 msec
CONTOURS = 2.0 BARS

TIME = 28.1 msec
CONTOURS = 1.0 BAR

TIME = 29.1 msec
CONTOURS = 1.0 BAR

TIME = 30.8 msec
CONTOURS = 1.0 BAR