Schwarz-1, Henry

ITEM 2

From: Bursian, Henry
Sent: Sunday, January 12, 2003 7:46 PM
To: PHG1; Wilhoit-1, Mike; Dibbern-1, Andreas
Subject: FW: Charts for 4:00 PRCB,

Follow Up Flag: Follow up
Flag Status: Flagged

BSTRA Balls3dw.ppt

WE HAVE OBTAIN A GO FOR LAUNCH FROM PROGRAM MANAGER. NEXT MILESTONE IS L-2 DAY. SEE ATTACHED CHARTS.

-----Original Message-----
From: Abner, Charlie
Sent: Sunday, January 12, 2003 7:22 PM
To: Bursian, Henry
Subject: FW: Charts for 4:00 PRCB

-----Original Message-----
From: ROE, RALPH R. (JSC-MV) (NASA) [mailto:ralph.r.roe@nasa.gov]
Sent: Sunday, January 12, 2003 4:58 PM
To: 'Rigby, David A'; Reith, Timothy W; Martingano, Trina A; Burghardt, Michael J; Christensen, Scott V; 'Curtis, Cris'; Dunham, Michael J; ALBRIGHT, JOHN D. (JSC-EP4) (NASA); ALLISON, RONALD L. (JSC-MV6) (NASA); APPLEWHITE, JOHN (JSC-EP) (NASA); BAIRD, R. S. (SCOTT) (JSC-EP) (NASA); BROWNE, DAVID M. (JSC-NC) (NASA); GRUSH, GENE R. (JSC-EP111) (NASA); JACOBS, JEREMY B. (JSC-ES4) (NASA); KRAMER, JULIE A. (JSC-EA4) (NASA); EXT-Madera, Pamela L; OUELLETTE, FRED A. (JSC-MV6) (NASA); TEMPLIN, KEVIN C. (JSC-MV6) (NASA); WAGNER, HOWARD A., PHD (JSC-EP) (NASA); EXT-White, Doug; Fineberg, Laurence H; Frazer, John W; Harrison, Steve; Mulholland, John P; Peller, Mark E; Pickens, Mark S; 'Saluter, Brett'; 'Snyder, Mike'; 'Stefanovic, Mike'; 'Young, Mike'; 'Paul Munafo (E-mail)'; 'alison.dinsel-1@ksc.nasa.gov'; 'srigby@houston.rr.com'; 'myoung10@cfl.rr.com'; RINGO, LESLIE A. (JSC-CB) (USA); ANTONELLI, DOMINIC A. (JSC-CB) (NASA); MELCHER, JOHN C. (JSC-DF55) (NASA); Collins, Thomas E; BENNETT, JAY E. (JSC-ES4) (NASA); 'Rick Russell (E-mail)'; MAYEAUX, BRIAN M. (JSC-ES4) (NASA); Lubas, Dave L; Solomon, Marcella; Wagner, Howard E; PREVETT, DONALD E. (DON) (JSC-EP) (NASA); MARTINEZ, HUGO E. (JSC-NC) (GHG); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); SHACK, PAUL E. (JSC-EA42) (NASA); LANE, WILLIAM F. (JSC-DF) (NASA); 'pelbg@ghg.net'; 'Don Blank (E-mail)'; 'Cris Curtis (E-mail)'; HERNANDEZ, JOSE M. (JSC-ES4) (NASA); 'Steven J. Gentz (E-mail)'; DINSEL, ALISON J. (JSC-ES5) (NASA); 'Lagart99@aol.com'; 'linda.combs@usahq.unitedspacealliance.com'; Hirakawa, Earl M; ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA); 'Rick Russell (E-mail)'; 'Charlie Abner (E-mail)'; Stenger-Nguyen, Polly; 'Linda Combs (E-mail)'; 'Don Blank (E-mail)'; 'Beil, Bob'
Cc: EXT-White, Doug; 'James Wilder (E-mail)'; Mulholland, John P; 'Mike Leinbach (E-mail)'
Subject: Charts for 4:00 PRCB

Attached.

dr

-----Original Message-----
From: Rigby, David A [mailto:David.A.Rigby2@boeing.com]
Sent: Sunday, January 12, 2003 6:59 AM
To: Reith, Timothy W; Martingano, Trina A; Burghardt, Michael J; Christensen, Scott V; 'Curtis, Cris'; Dunham, Michael J; ALBRIGHT, JOHN D. (JSC-EP4) (NASA); ALLISON, RONALD L. (JSC-MV6) (NASA); APPLEWHITE, JOHN (JSC-EP) (NASA); BAIRD, R. S. (SCOTT) (JSC-EP) (NASA); BROWNE, DAVID M. (JSC-NC) (NASA); GRUSH, GENE R. (JSC-EP111) (NASA); JACOBS, JEREMY B. (JSC-ES4) (NASA); KRAMER, JULIE A. (JSC-EA4) (NASA); EXT-Madera, Pamela L; OUELLETTE, FRED A. (JSC-MV6) (NASA); TEMPLIN, KEVIN C. (JSC-MV6) (NASA); WAGNER, HOWARD A., PHD (JSC-EP) (NASA); EXT-White, Doug; Fineberg, Laurence H; Frazer, John W; Harrison, Steve; Mulholland, John P; Peller, Mark E; Pickens, Mark S; 'Saluter, Brett'; 'Snyder, Mike'; 'Stefanovic, Mike'; 'Young, Mike'; 'Paul Munafo (E-mail)'; 'alison.dinsel-1@ksc.nasa.gov'; 'srigby@houston.rr.com'; 'myoung10@cfl.rr.com'; RINGO, LESLIE A. (JSC-CB) (USA); ANTONELLI, DOMINIC A. (JSC-CB) (NASA); MELCHER, JOHN C. (JSC-DF55) (NASA); Collins, Thomas E; BENNETT, JAY E. (JSC-ES4) (NASA); 'Rick Russell (E-mail)'; MAYEAUX, BRIAN M. (JSC-ES4) (NASA); Lubas, Dave L; Solomon, Marcella; Wagner, Howard E; PREVETT, DONALD E. (DON) (JSC-EP) (NASA); MARTINEZ, HUGO E. (JSC-NC) (GHG); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); SHACK, PAUL E. (JSC-EA42) (NASA); LANE, WILLIAM F. (JSC-DF) (NASA); 'pelbg@ghg.net'; 'Don Blank (E-mail)'; 'Cris Curtis (E-mail)'; HERNANDEZ, JOSE M. (JSC-ES4) (NASA); 'Steven J. Gentz (E-mail)'; DINSEL, ALISON J. (JSC-ES5) (NASA); 'Lagart99@aol.com'; 'linda.combs@usahq.unitedspacealliance.com'; Hirakawa, Earl M; ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA); 'Rick Russell (E-mail)'; 'Charlie Abner (E-mail)'; Stenger-Nguyen, Polly; 'Linda Combs (E-mail)'; 'Don Blank (E-mail)'; 'Beil, Bob'
Cc: ROE, RALPH R. (JSC-MV) (NASA); EXT-White, Doug; 'James Wilder (E-mail)'; Mulholland, John P; 'Mike Leinbach (E-mail)'
Subject: RE: Tagups for the next 3 days

FYI.

The Sunday start time is moved up to 12:00 Noon. Same Number.

PRCB is scheduled for 4:00 PM CST Sunday. Not on this number, but instead via normal PRCB tie in only.

dr

> -----Original Message-----
> From: Reith, Timothy W
> Sent: Thursday, January 09, 2003 10:45 AM
> To: Reith, Timothy W; Martingano, Trina A; Rigby, David A; Burghardt, Michael J; Christensen, Scott V; 'Curtis, Cris'; Dunham, Michael J; EXT-Albright, John D; EXT-Allison, Ronald L; EXT-Applewhite, John ; EXT-Baird, R SCOTT; EXT-Browne, David M; EXT-Grush, Gene R; EXT-Jacobs, Jeremy B; EXT-Kramer, Julie A; EXT-Madera, Pamela L; EXT-Ouellette, Fred A; EXT-Templin, Kevin C; EXT-Wagner, Howard A; EXT-White, Doug; Fineberg, Laurence H; Frazer, John W; Harrison, Steve; Mulholland, John P; Peller, Mark E; Pickens, Mark S; 'Saluter, Brett'; 'Snyder, Mike'; 'Stefanovic, Mike'; 'Young, Mike'; 'Paul Munafo (E-mail)'; 'alison.dinsel-1@ksc.nasa.gov'; 'srigby@houston.rr.com'; 'myoung10@cfl.rr.com'; 'Leslie Ringo (E-mail)'; 'Tony Antonelli (E-mail)'; 'JC MELCHER (E-mail)'; Collins, Thomas E; EXT-Bennett, Jay E; 'Rick Russell (E-mail)'; 'brian.m.mayeaux@nasa.gov'; Lubas, Dave L; Solomon, Marcella; Wagner, Howard E; EXT-Prevett, Donald E; EXT-Martinez, Hugo E; EXT-Seriale-grush, Joyce M;!
EXT-Shack, Paul E; 'Bill Lane (E-mail)'; 'pelbg@ghg.net'; 'Don Blank (E-mail)'; 'Cris Curtis (E-mail)'; 'jose.m.hernandez@nasa.gov'; 'Steven J. Gentz (E-mail)'; 'alison.j.dinsel@nasa.gov'; 'Lagart99@aol.com'; 'linda.combs@usahq.unitedspacealliance.com'; Hirakawa, Earl M; EXT-Rocha, Alan RODNEY; 'Rick Russell (E-mail)'; 'Charlie Abner (E-mail)';

Stenger-Nguyen, Polly; 'Linda Combs (E-mail)'; 'Don Blank (E-mail)'; 'Beil, Bob'
> Cc: 'Ralph Roe (E-mail)'; EXT-White, Doug; 'James Wilder (E-mail)'; Mulholland, John P; 'Mike Leinbach (E-mail)'
> Subject: Tagups for the next 3 days
>
> We will have a daily status call at 1 pm Central on Fri, Sat, & Sun. Agenda will include
>
> updates on testing
> ball NDE & DE
> FOD evaluation
> PRA status
>
> On Fri, Dave has asked the SSME Project to present their assessment on FOD impacts.
>
> Call in is the same
>
> 1-877-987-0469 pc 692086

SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

OV103 Cracked BSTRA Ball Discussion

Overview

- BSTRA Team has been able to significantly increase our knowledge of BSTRA ball material (Stoody #2) characteristics, tendency to crack and performance once cracked.
- Our current inspections indicate only 1 confirmed crack in 54 ball inspections.
- However, the team believes our eddy current and CAT scan inspections of the spare population with sub-surface flaws is more representative of the number of cracks we may experience in the fleet (8/27).
- Tests performed on eight different BSTRA balls have several conservative aspects.
  - All balls under test were forced to crack. Vehicle population should be more consistent with spare population that have a tendency to crack due to sub-surface flaws (7/27).
  - The temperature gradient (strain) used to crack "severely" cracked balls was greater than the flight environment.
  - Test balls were cracked with entire sphere exposed to thermal gradients, creating stresses on entire sphere. Flight balls are insulated by cups and largest gradients and stresses are confined to exposed surface area.

Overview

- Tests performed on eight different BSTRA balls have several conservative aspects. (cont'd)
    - Once cracked, test balls were exposed to 4+ times current flight mechanical cycles and 2+ times current flight thermal cycles.
    - Once cracked, test balls were oriented for worse case stresses to continue to grow crack and produce FOD.
- To date we have completed testing, inspection and documentation of 4 test balls
    - Cracks arrest
    - BSTRA ball cracks do not limit functionality
    - Many features, islands, branching, fines and FOD, observed.
    - No FOD > 400 micron, equivalent size produced
- SSME community has established the limits for FOD size and quantity based on flight experience and design limitations.
- Stress Team has developed model which agrees with our observations and substantiates the conservatism of our testing.
- M&P Team has observed metallurgical characteristics that indicates the jagged nature of the fracture provides a locking feature to preclude large island liberation

Overview

- PRA Model has been developed by constraining ourselves to "the observed facts". Models define risk to be within existing level of Program risk for LOCV.

- Conclusions
  - BSTRA ball testing is conservative
  - BSTRA balls in the fleet may be cracked.
  - BSTRA ball cracks will arrest.
  - BSTRA balls with cracks will continue to perform function.
  - BSTRA ball cracks will generate FOD.
  - BSTRA ball FOD size and quantity is within acceptable limits.
  - Risk of BSTRA ball FOD is within existing Program risk levels.
  - Testing on 4/8 balls complete to date confirms each of these statements.

- **The Question we must ask ourselves is:**

  Have we tested enough BSTRA balls to envelope anything we may see in flight?

Goal of this Presentation:

- Provide an update to the SSP on the status of testing and analysis activities to support flight rationale
- Provide recommendation to start countdown based on confidence of data to date

Agenda:

- Stress Analysis Update
- Margin / Conservatism of Testing
- Status of Testing
- Crack Arrest Testing and Rationale
- Joint Angulation Binding Testing and Rationale
- FOD
    - SSME Tolerance to FOD
    - Testing Results Review
    - PRA
- KSC Inspection Update
- Conclusions

Flight Rationale Based on Resolution of Two Issues

- Joint performance with cracked balls
  - Cracks must be self-limiting
    - Ball remains intact
    - Load margins remain positive
  - Joint angulation capability not compromised
    - Friction
    - Binding
- FOD from cracked balls
  - Crack propagation does not create FOD
  - No spalling

Stress Analysis Update

- Significant cracks due to severe thermal shock can be considered an upper bound
  - Thermal gradients used to develop initial cracks actually represent an upper bound of flight environment
    - Especially 1.25 inch LH2 balls
    - 1.75 and 2.24 inch balls were relatively extreme compared to the LO2 flight environment
  - 1.75 inch ball with naturally induced crack eventually produced similar significant crack during thermal cycling
  - With two exceptions, cracks were induced at initial temperatures of 300 degrees or below

Stress Analysis Update (cont)

- Bare balls in thermal shock produce significant stresses over entire surface
  - A ball installed in cups leave a small percentage of the ball surface area exposed
    - 50 percent higher stresses than a bare ball, but over a smaller zone at the equator
    - Mechanical stresses are lower due to compression by cups
- Thermally induced cracks are self relieving (but deep)
- Tight fit between ball and cups produce large compression zones over most of ball
  - Only small low stress tension zones on equator of ball outside of the cups are present to grow cracks mechanically
  - Compression zones tend to limit crack propagation

Margin / Conservatism of Testing

- Dynamic portion of each loading cycle represents approximately 4x actual environment
- Cyclic loading: 4x nominal load cycles / 2x thermal
- Load levels: 1.5x and 1.75x nominal load levels
- LN2 to represent LO2 is 50% higher thermal gradient
- High temp to glycol / dry ice is a more severe thermal gradient than the LH2 environment

Testing Status Summary

Ball Size	Total	Severely Cracked Balls	Less Severely Cracked Balls	Naturally Cracked Balls
2.24”	4	3	1	0
1.75”	2	1	0	1
1.25”	2*	2	0	0

* Second severely cracked ball produced while attempting to create less severely cracked ball with dual EDM notch

- Eddy current and CT scan of spare balls produced additional test samples with indications
  - 2.24 inch: 1 in LN2 cycling to initiate a natural crack
  - 1.75 inch: 3 in LN2 cycling to initiate a natural crack
  - 1.25 inch: 2 in LN2 cycling to initiate a natural crack

Testing Status Summary

- 2.24 inch balls
  - 4 of 4 testing complete / in destructive testing for M&P characterization
- 1.75 inch balls
  - 1 of 2 testing complete / in destructive testing for M&P characterization
  - ECD 1/13/03
- 1.25 inch balls
  - Using 300 F (oven) to –65 F (glycol / dry ice) to simulate LH2 thermal profile
  - 0 of 2 complete
  - ECD 1/14/03 for first ball
  - ECD 1/17/03 for second ball

Cracks Must Be Self-Limiting

- Testing status
  - Crack arrest shown for all cases
- Thermally induced cracks are self-relieving
- Tight fit between ball and cups produce large compression zones over most of ball
  - Only small low stress tension zones on equator of ball outside of the cups are present to grow cracks mechanically
  - Compression zones tend to limit crack propagation

MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

Joint angulation capability not compromised

- Friction
- Binding
- For all balls with cracks, vertical offset between surfaces will be measured
  - Initial work on a severely cracked 2.24 inch ball by MSFC M&P showed no issue
    - Measured 180 microinches offset maximum
    - 500 microinch vitrolube thickness minimum
  - Friction testing in-work on 2.24 inch ball
    - Offset less than vitrolube thickness
    - ECD 1/12/03

BSTRA Ball FOD Testing

- System design limits
  - Oxygen: 800 microns
  - Hydrogen: 400 microns
  - Prevalve screen: 1000 microns
    - 17” line upstream of screen
    - 12” line downstream of screen
  - Actions to determine acceptability of FOD with the SSME project complete

SSME FOD Assessment

January 12th, 2003
Phin Jones

MPS BSTRA Ball FOD Assessment

- Issue
  - MPS BSTRA ball cracking may liberate particles of Stoody 2 material into engine inlet
- Background
  - SSME designed for particle ingestion of 400 micron max fuel system and 800 max lox system
    - Size smaller than smallest SSME orifice
      - Particles pass through with no detrimental effects
      - OPB injector contains smallest orifice

        Oxygen orifice equal to 0.038 inches (970 microns)

        Fuel orifice equal to 0.018 inches (460 microns)
- Assessment

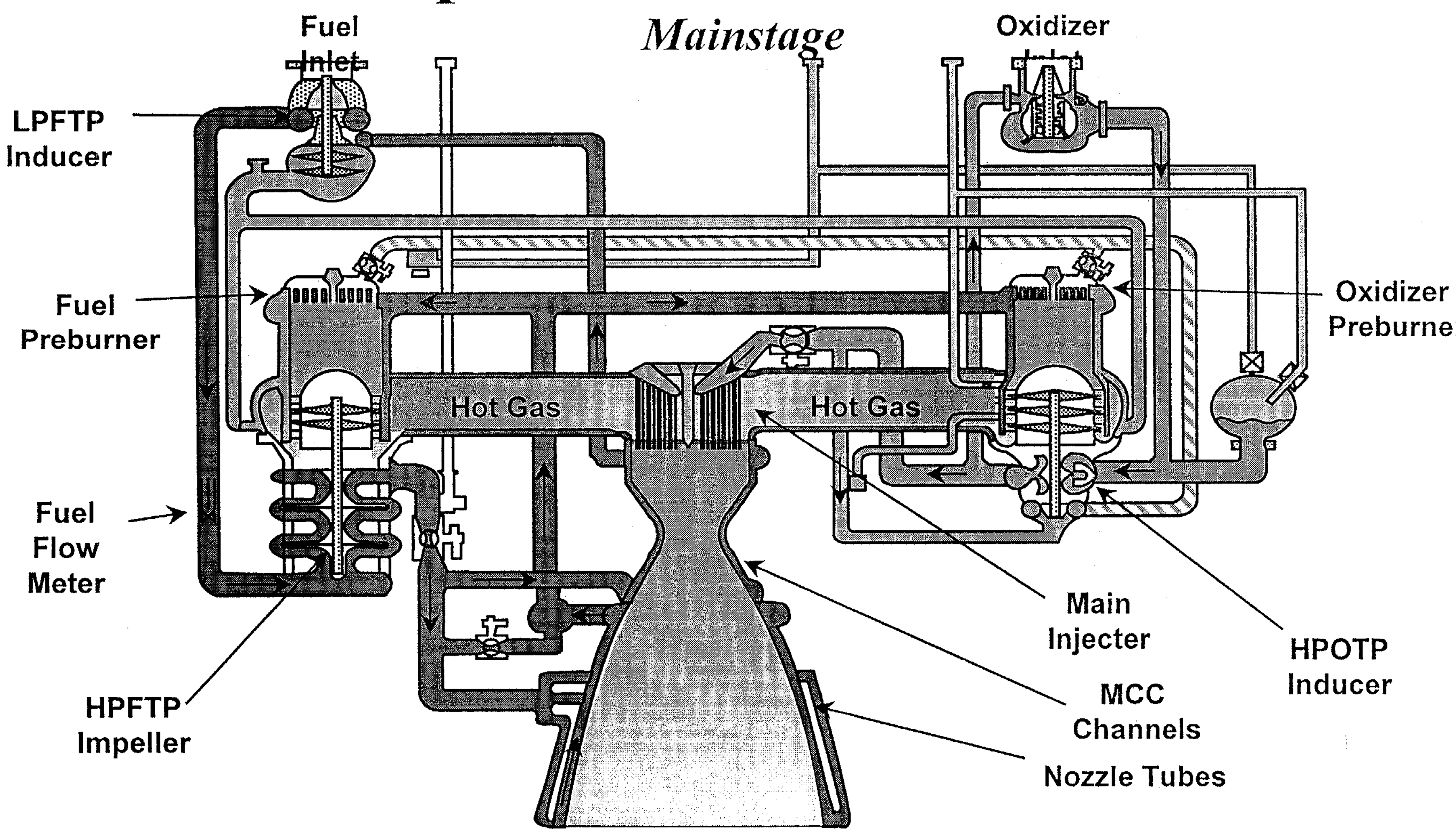
  (1) Determine minimum particle size capable of damaging engine hardware

  (2) Determine effect of accumulation of particles between design and critical size

Effect of Stoody 2 FOD on SSME

- SSME design demonstrated at CEI cleanliness requirements
  - Particles up to 400 fuel / 800 ox microns pass through engine with no detrimental effects
    - Stoody 2 spherical mass
      - 400 microns = 0.0003 grams
      - 800 microns = 0.0023 grams
  - No orifices smaller than CEI requirements
  - Test stand engine inlet filters
    - 275 microns fuel
    - 710 micron ox

Simplified SSME Schematic



Effect of Stoody 2 FOD on SSME
Impact Damage/Ignition

(1) Determine minimum particle size capable of damaging engine hardware

- Large mass impact can induce stress equal to the ultimate strength of material
  - Crit 1 condition: impact liberates SSME material
  - Estimated minimum mass impacting HPFTP impeller
    - 0.7 grams or 5350 micron sphere of Stoody 2
- Impact Ignition results from particle impact in oxygen system
  - Crit 1 condition: spark weakens material, continued operation fatigues material, material liberated
  - Estimated minimum mass impacting HPOTP inducer
    - 0.028 grams or 1800 micron sphere of Stoody 2

Effect of Stoody 2 FOD on Fuel System
Accumulation/Blockage

(2) Determine effect of accumulation of particles between design and critical size in the Fuel System

- MCC channel blockage results in liner crack and leakage
  - MCC channel min dimension = 0.034 inches (875 microns)
    - 24 channels blocked = 6 lbs/sec fuel leak
- Nozzle tube blockage results in tube rupture
  - Minimum forward end tube dia. = 0.051 inches (1300 microns)
    - 10 forward end ruptures = 6 lbs/sec fuel leak
- Preburner post fuel orifice blockage results in increased local mixture ratio
  - Minimum fuel sleeve orifice = 0.018 inch (460 microns)
    - 100 holes on a single post blocked damages turbine hardware
    - Local heating may escape redline detection crit 1

Effect of Stoody 2 FOD on LOX System
Accumulation/Blockage

(2) Determine effect of accumulation of particles between design and critical size in the LOX System

- Main Injector post LOX orifice partial blockage results in post burn through and subsequent extensive erosion – crit 1
  - Minimum LOX post orifice = 0.098 inches (2500 microns)
    - 1 partially plugged post orifice results in crit 1 condition

- Ox Preburner post LOX orifice blockage results in increased OPOV command
  - Minimum LOX post orifice = 0.038 inch (970 microns)
    - 20 plugged posts result in command limiting, loss of thrust

Summary

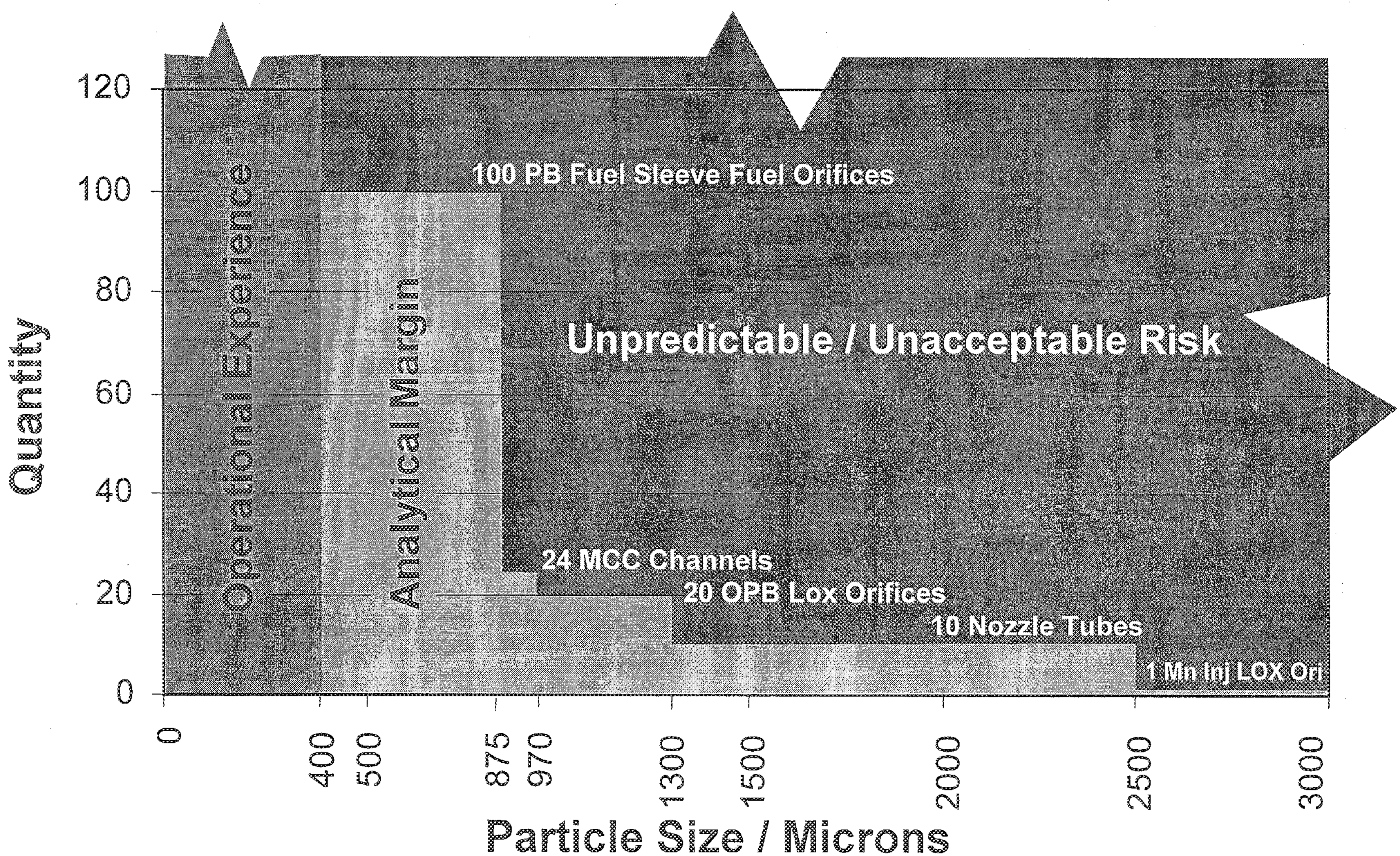
• Fuel and LOX System Particle Size Summary

		Impact	Accumulation/Blockage		
SSME System	Design Max Particle Size (Micron)	Minimum Particle Mass for SSME Damage, Crit 1	Min Particle Quantity/2D Size for Significant Blockage	Min Particle Quantity/2D Size for significant blockage	Min Particle Quantity/2D Size for significant blockage
Fuel System	400	0.7 grams	10/1300 micron (1)	24/875 micron (2)	100/460 micron (3)
LOX System	800	0.028 grams	1/2500 micron (4)	20/970 micron (5)	

(1) Nozzle tube rupture (assume spheres then mass = 0.101 grams)
(2) MCC channel blockage (assume spheres then mass = 0.08 grams)
(3) OPB fuel sleeve blockage (assume spheres then mass = 0.044 grams)
(4) MCC lox orifice blockage (assume spheres then mass = 0.072 grams)
(5) OPB lox orifice blockage (assume spheres then mass = 0.048 grams)

Particle Accumulation
Blockage

Presenter Phin Jones
Date Jan. 2003



Conclusion

- Conclusion
  - Particle size of 400/800 microns proven safe for SSME operation
  - Particle mass >0.028 grams unacceptable due to impact ignition
  - Particle sizes greater than design limits increase mission risk, catastrophic risk, and may decrease hardware life
    - Accumulation of any particles increases risk
      - Particles > 460 microns will accumulate in Fuel System
      - Particles > 970 microns will accumulate in LOX System

Backup

Critical Impact Mass Assessment

Fuel System Component	Critical Impact Mass (grams)	Sphere of Stoody 2 diameter (Microns)	Comments
LPFTP Inducer	0.83	5700	Blade stress = ultimate strength of material
HPFP Impeller	0.7	5350	Vane stress = ultimate strength of material
Fuel Flowmeter	0.51	4800	Blade damage could result in Kf shift
Oxygen System Component			
LPOP Inducer	2.48	8000	Blade stress = ultimate strength of material
HPOP Inducer	0.49	4750	Vane stress = ultimate strength of material
HPOP Impeller Tip Impact ignition	0.028	1800	750 ft/sec impact on Inconnel 718

MPS BSTRA Ball FOD Assessment
Cleanliness Requirements

- Fuel System
  - Maximum particle size per CEI is 400 microns = 0.016 in.
    - Derived from preburner Fuel injector orifices
      - OPB 120 posts, 168 orifices, 0.018 inch dia
      - FPB 264 posts, 168 orifices, 0.018 inch dia
- LOX System
  - Maximum particle size per CEI is 800 microns = 0.031 in.
    - Derived from preburner LOX injector orifices
      - OPB 120 LOX injector orifices, 0.038 inch dia
      - FPB 258 LOX injector orifices, 0.042 inch dia
- GOX system
  - Orbiter GOX system CEI requirement = 100 microns
  - Protected by SSME AFV 100 micron filter

BSTRA Ball FOD Testing (cont)

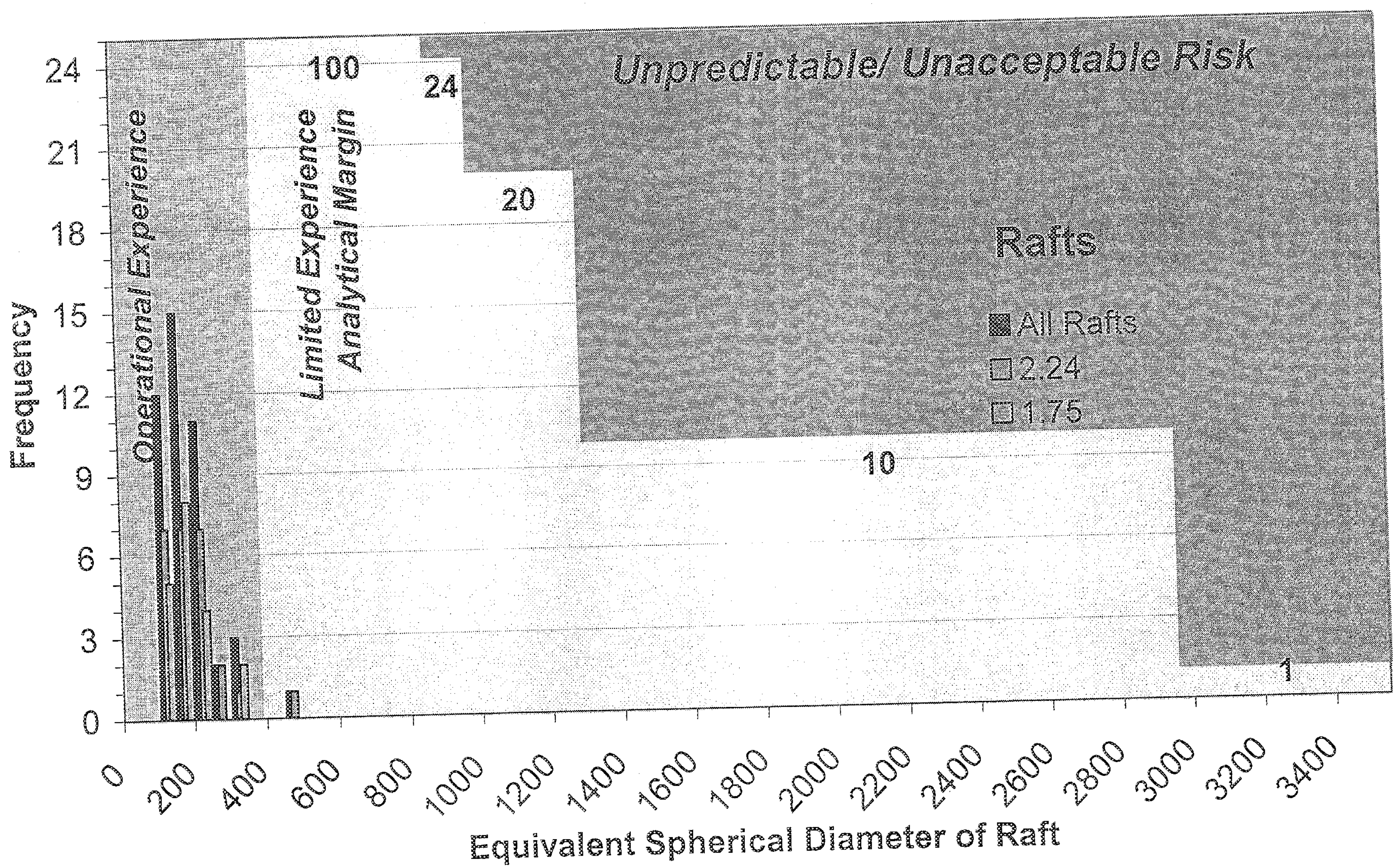
- Issues with severely cracked balls
  - Branching cracks
  - Material islands
  - Loss of parent material

Type of cracks	Total Samples	Balls with Branching Cracks	Balls with Material Islands	Balls with Loss of Parent Material
Severe	6	6	6	4
Less Severe	1	0	0	0
Natural	1	1	1	1

BSTRA Ball FOD Testing (cont)

- Definitions
  - Islands are parallel cracks creating an area of parent material between them which start from and rejoin to the original crack
  - Rafts are liberated islands, either in part or in whole
  - Fines are loss of material along the crack, which may or may not be associated with an island

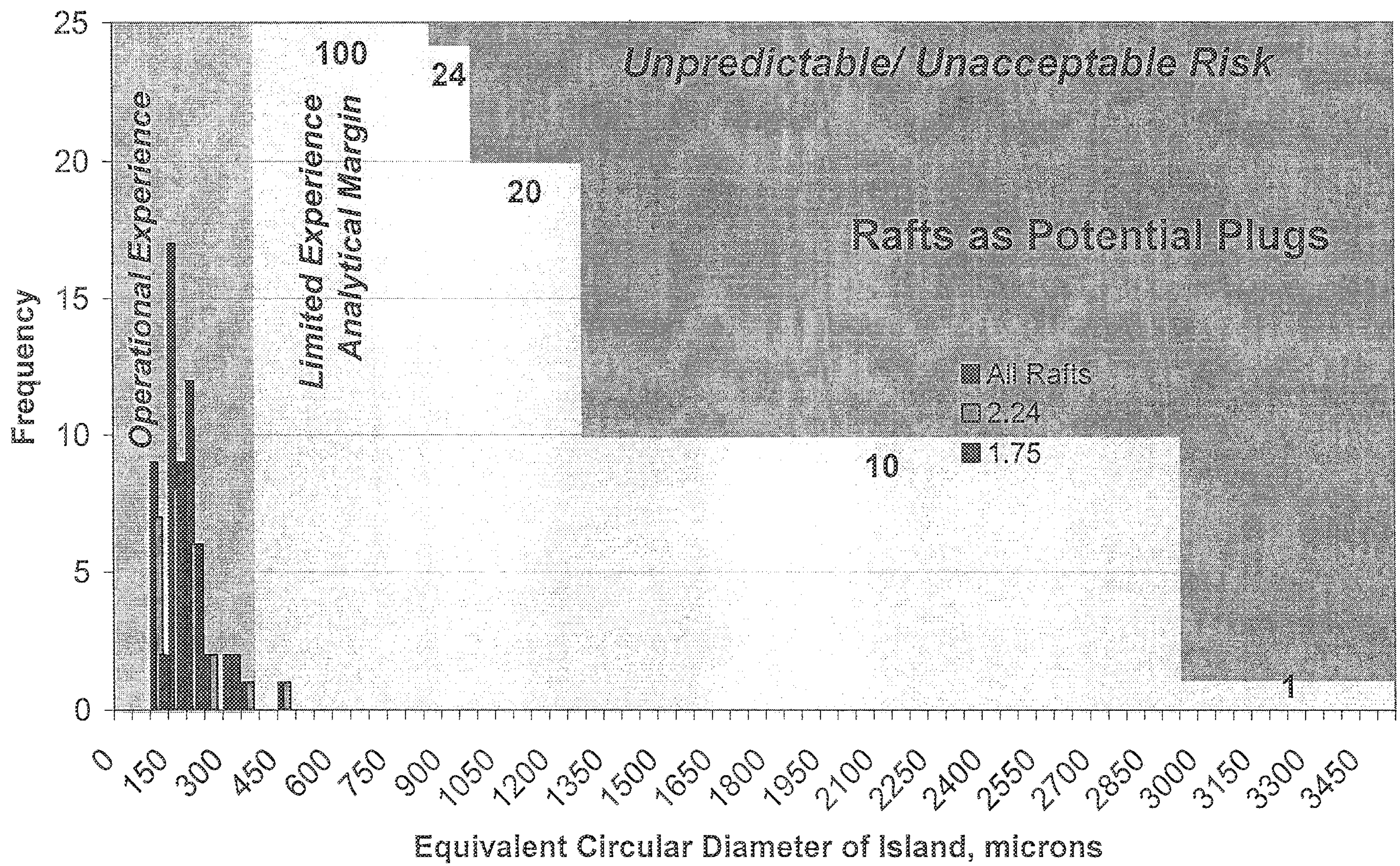
Rafts/ Particle Accumulation



Rafts/ Particle Accumulation: Plugs

Presenter David Rigby

Date Jan. 2003



Characterization Program to Support Orbiter OV-103 BSTRA "Stoody #2" Ball Crack Indication

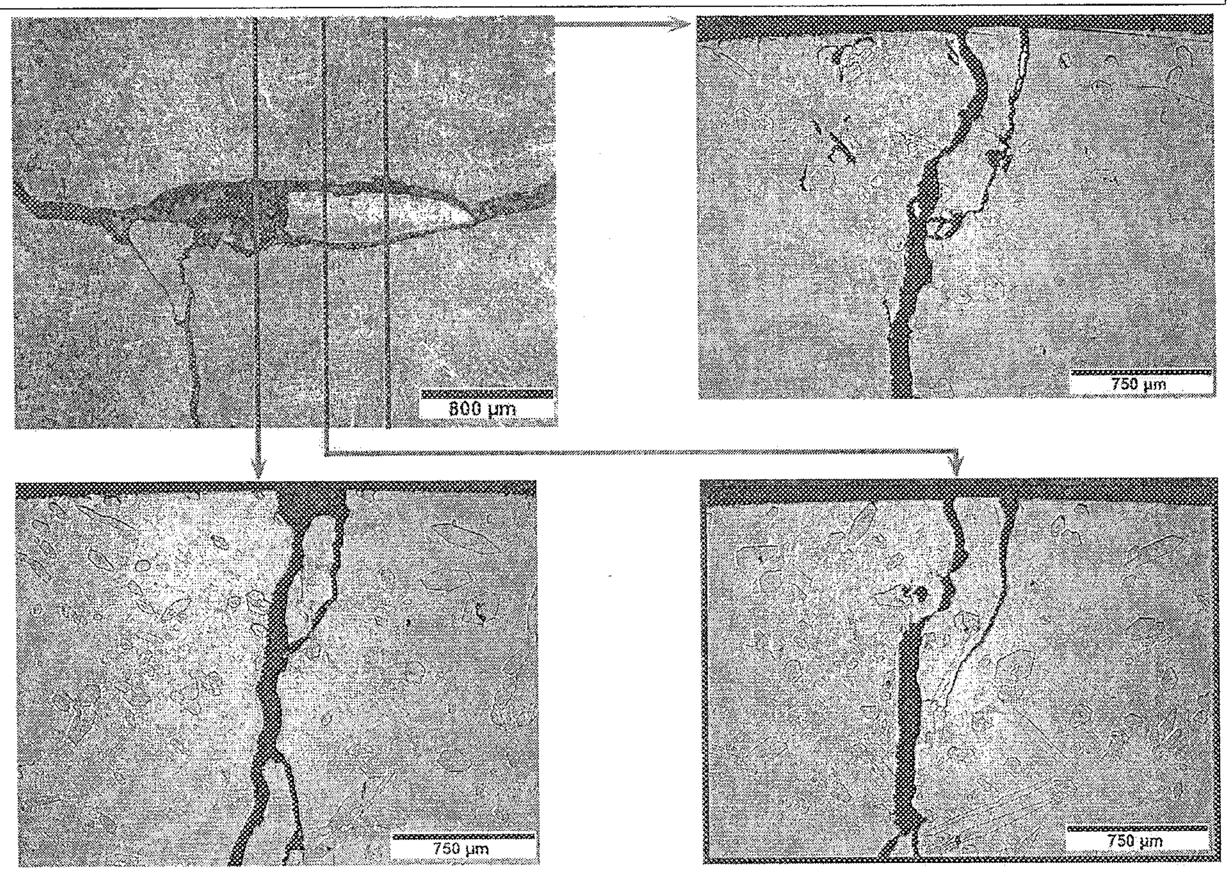
Metallurgical Factors that Limit Size of FOD Liberated from Islands

Predictable by microstructure and confirmed by observation

- "Jigsaw Puzzle Piece", nature of mating crack surface
- Surface "Roughness", to inhibit ejection of a large island
- Small particles, near the surface, resulting from "grinding" action (combined shear + compression)

MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

MSFC-2.24-1 Metallographic Sectioning

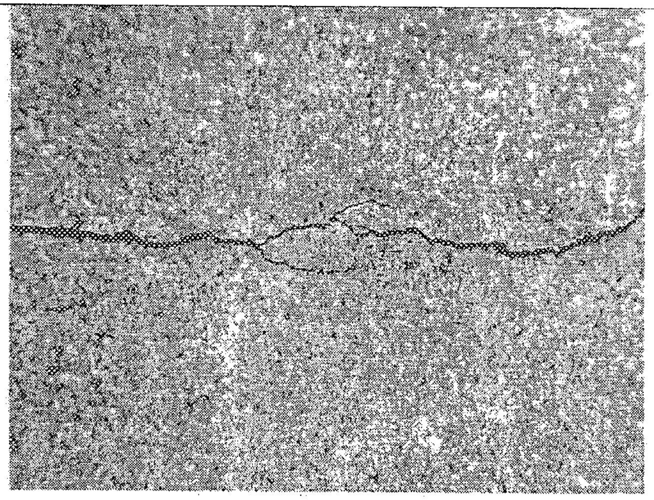


Metallurgical Factors that Limit Size of FOD Liberated from Islands (continued)

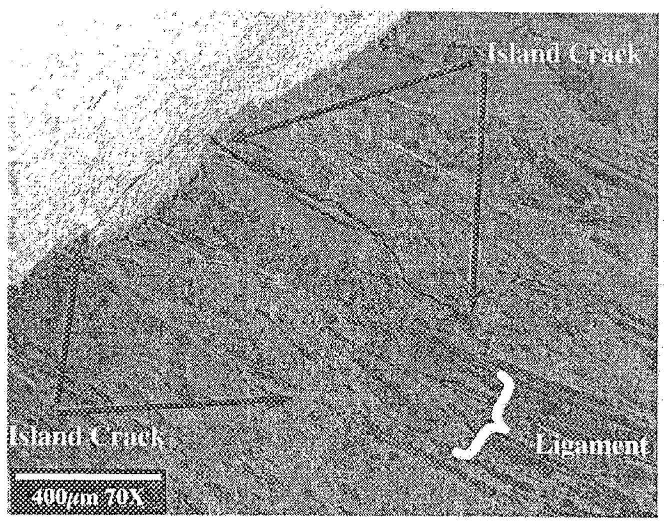
- **Direct Observation of Characteristics of a Running Crack**
  - Dynamic nature of secondary cracking process that causes island formation also produces cracks in the two orthogonal planes
  - Deep islands are physically rooted at the base, or on one surface

MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

MSFC-1.75-2 Island Fractography



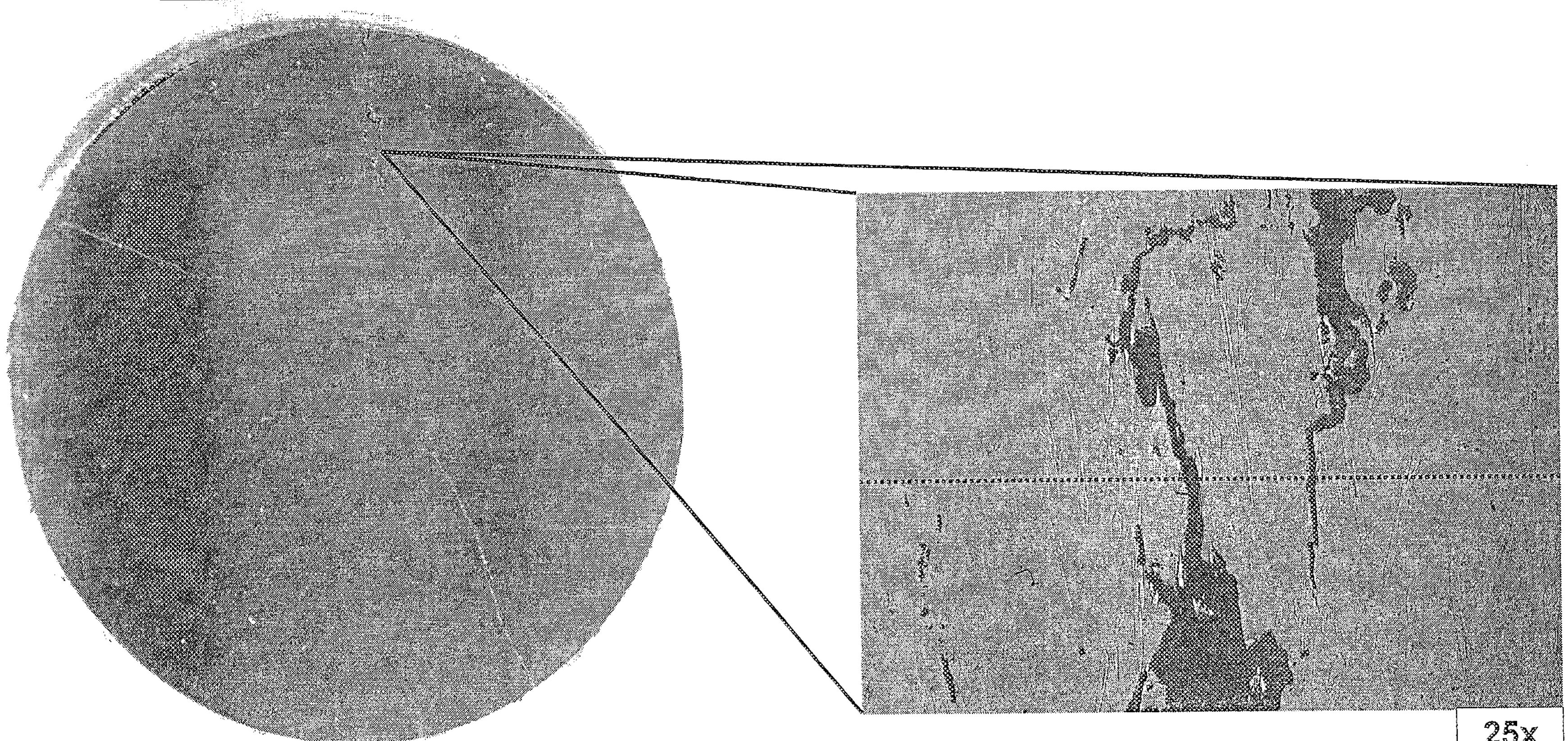
Optical Observation of Potential FOD Island During 1.75 Inch Diameter Ball Compression Testing



SEM Observation of Potential FOD Island After Opening the Main Crack

MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

MSFC-2.24-1 Metallographic Sectioning



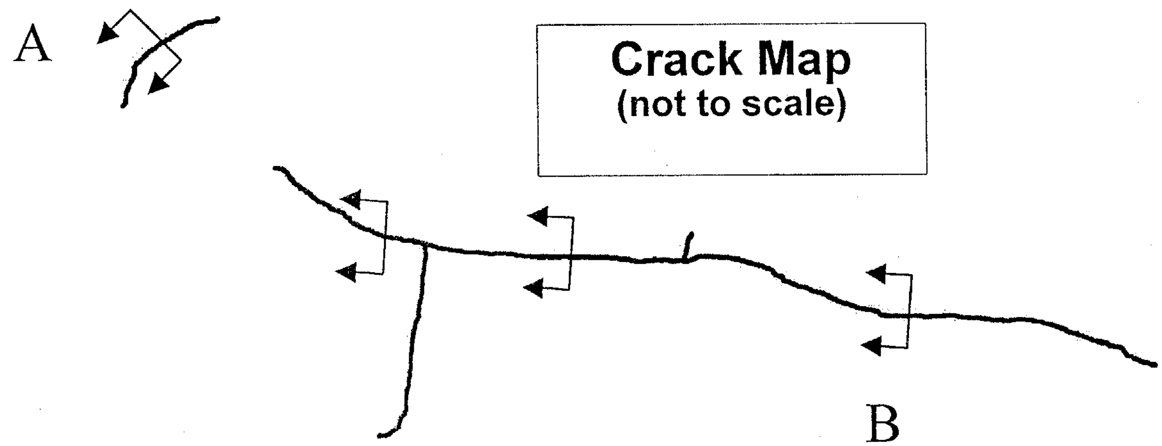
25x

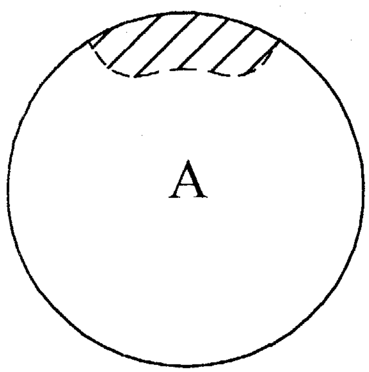
Half Section

MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

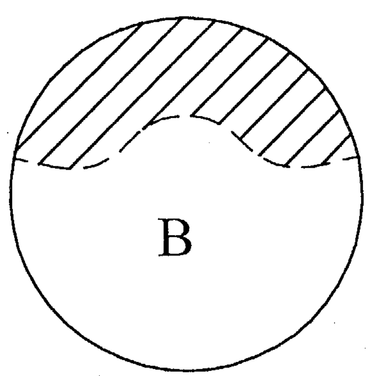
MSFC-1.75-2 Crack Depth Analysis

Crack Map
(not to scale)



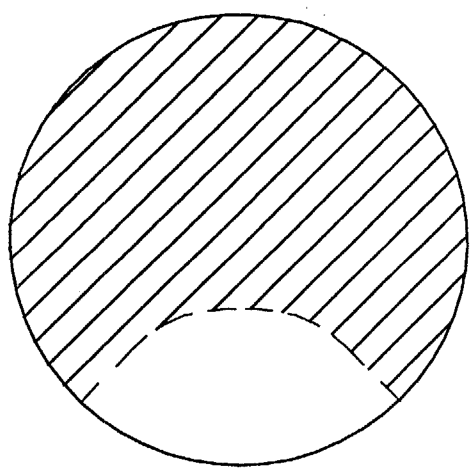


Section Map
(to scale)



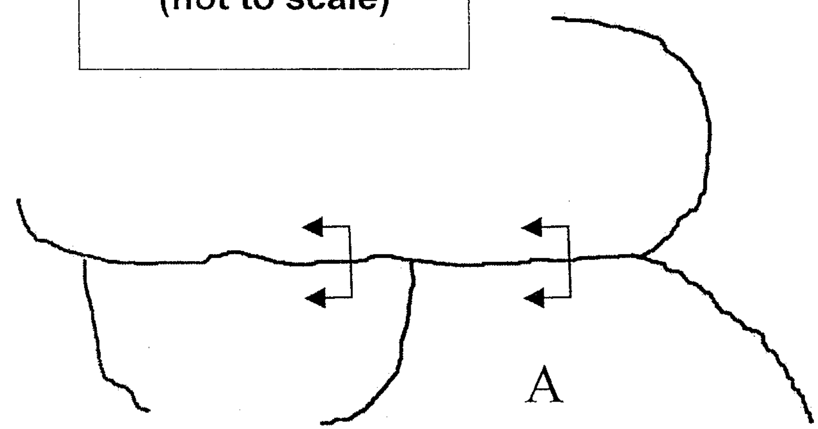
MPS 17" Feedline Ball Strut Tie Rod Assembly Ball Crack

MSFC-2.24-1 Crack Depth Analysis



Section Map
(to scale)

Crack Map
(not to scale)



Event Sequence

Critical SSME Damage

Passes thru SSME

} Assumed to be occur

Exposed Raft — What is the likelihood that a raft is exposed to the flow?

>400μ FOD — What is the likelihood that a raft of 400μ or larger is released?

Crack Frequency — What is the likelihood of having a crack per mission?

Mission Risk Comparison

Nominal Shuttle Mission Risk
(Based on QRAS 2000)

- Ascent
  - Mean ~ 1 in 517 missions
  - Median ~ 1 in 557 missions
  - 5^{th} ~ 1 in 900 missions
  - 95^{th} ~ 1 in 310 missions
- Total Mission Mean ~ 1 in 265 missions

BSTRA Raft Mission Risk

- Median < 1 in 200,000 missions
- 95th < 1 in 20,000 missions

OV-103 BSTRA Ball Inspection Update

- Initial attempts to rotate the ball were unsuccessful with and without the BSTRA compression load tool
  - Shear load on the ball prevented rotation
- Translated 17" umbilical to remove shear load without going out of OMRSD / design family of experience and freed ball
- Islands and fines noted
- Crack length being determined
- ECD 1/12/03

Conclusions

- BSTRA ball testing is conservative
- BSTRA balls in the fleet may be cracked
- BSTRA ball cracks will arrest
- BSTRA balls with cracks will continue to perform function
- BSTRA ball cracks will generate FOD
- BSTRA ball FOD size and quantity is within acceptable limits
- Risk of BSTRA ball FOD is within existing Program risk levels
- Testing on 4/8 balls complete to date confirms each of these statements

- **The Question we must ask ourselves is:**

  Have we tested enough BSTRA balls to envelope anything we may see in flight?

SSVEO Position

- Testing to date represents an equivalent population size of about 13 balls. Which represent about 18% of vehicle population. This is an adequate sample from which to draw our conclusions.
  - Vehicle population 72,
  - Spares 8/27 with flaws that may become cracks
  - 4/8 test balls cracked and completed testing

- Based on our conservative testing, this is an acceptable risk however, we are generating FOD and overtime this could increase to an unacceptable level, either quantity or size. We would continue to have to test to evaluate this as we continue to fly.
- Therefore we should move out on techniques to identify cracked balls and remove and replace on a opportunity basis and continue to fly within the limits of our testing experience. 4 times mechanical and 2 times thermal cycles.