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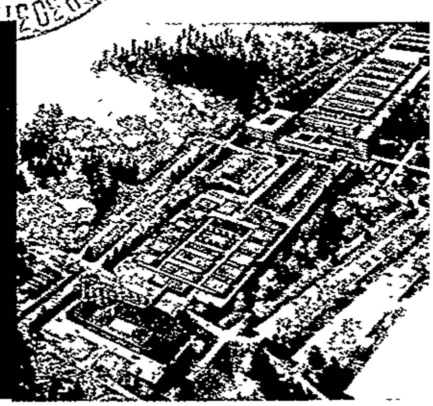

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MARINER JUPITER/SATURN LCSSE THRUSTER/VALVE ASSEMBLY AND INJECTION PROPULSION UNIT ROCKET ENGINE ASSEMBLIES

0.2-lbf T/VA Development and Margin Limit Test Report

Contract No.: 954108

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Submitted To:

California Institute of Technology
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1.0 SCOPE

On 20 January 1976, a special study team was organized to investigate and resolve the capillary tube plugging phenomena on the 0.2-lbf T/VA. These activities and their results must be considered a part of the T/VA development program. This report is therefore being submitted as an addendum to the T/VA Development and Margin Limit Test Report (RRC-76-R-499, dated 12 December 1975).

In order to accomplish these activities in a timely manner supporting the overall MJS '77 Program, five principal areas of concern were simultaneously investigated. Details of each of these studies are presented together with their conclusions.

2.0 INTRODUCTION

Action item number 9 of the Preliminary Design Review on the T/VA Program held 16 January 1975, requested an evaluation of the impact of vibration in the nozzle up attitude. This request was prompted by two considerations:

(a) Certain pitch thrusters on the MJS '77 vehicle would be oriented at 45 degrees off the nozzle up attitude.

(b) The first user of the LCSSE T/VA, the Global Positioning Satellite Program, had oriented approximately half of the thrusters in a nozzle up attitude, and were conducting all assembly environmental tests in this attitude.

On 21 February 1975, it was determined that all future vibration testing be conducted in the nozzle up attitude. However, in the interest of minimum schedule impact, the development units (S/N D01 and D02) were acceptance tested (FA) in the horizontal attitude. This change was technically acceptable based upon the fact that an ATS engine had successfully demonstrated nozzle up vibration as well as the ongoing GPS Program. As discussed in the main portion of this report, the two T/VA development units were subjected to extensive nozzle up environmental testing without incident.

On 23 October 1975, during acceptance testing of the first two qualification T/VAs, one unit failed to fire (F/N 029). A detailed failure investigation identified blockage of the capillary tube as the cause of not firing. This blockage was subsequently identified as catalyst. Since these two units had been the first T/VAs to be subjected to nozzle up acceptance vibration, and the development T/VAs had successfully withstood nozzle up qualification vibration, it was postulated that fines from packing were migrating through the injector screen and subsequently plugging the capillary tube. A minimum cost change to try to eliminate these fines was instituted. This change consisted of water flushing the packed injector assembly immediately after welding.

On 4 December 1975, an identical failure to fire occurred (F/N 024) on one of eight flight T/VAs fabricated with this new procedure. An identical failure investigation confirmed catalyst plugging of the capillary tube. In order to preclude the reoccurrence of such a failure in the firing setup, a gas flow check for capillary tube plugging was instituted between vibration and firing on the next four T/VAs. As a result of improper implementation on one of these T/VAs (F/N 026), excessive valve gas leakage was detected during firing preparations. Failure analysis of this valve (FAR 10030) revealed particulate (catalyst) contamination of the valve seat.

Although a particle count of the water flushed through a packed injector assembly indicated a large quantity of catalyst fines (Table 2-1), it was demonstrated on F/N 024 and 026 that there were fines remaining following vibration. It was then postulated that the water flush velocity was insufficient to clear all packing fines and that the program should be rebaselined with a pre-vibration hot firing replacing the water flush. Confidence in this approach was established from the two T/VAs on the development test program and the qualification test article (F/N 045). This unit, which had been tested with F/N 029 and successfully acceptance fired, had subsequently been subjected to the full qualification level vibration spectrum and verified by gas flow check to be clear. A summary of all RRC 0.2-/0.1-lbf nozzle up vibration tests is presented in Table 2-2.

In order to verify the adequacy of this plan and establish confidence in the flight worthiness of the basic design, the special study program was initiated. The study was initially divided into the following five major areas of investigation:

- (a) F/N 024 and 029 Teardown
- (b) Capillary Tube Investigation
- (c) Design Studies
- (d) Catalyst Strength Study
- (e) Packing Studies

TABLE 2-1

Particle Count of Water Flushed

Through Packed Injector

Size	Number of Particles
5 - 10 Microns	52
11 - 25 Microns	51
26 - 50 Microns	49
51 - 100 Microns	17
101 - 125 Microns	1
> 125 Microns	5

TABLE 2-2

0.2-lbf / 0.1-lbf Nozzle Up Vibration History

Program	Number of Engines	Type of Vibration	Number of Axes Tested	Maximum Input To Catalyst Bed	(Axis)	Remarks
ATS	1	Random	3	90 grms	(Y)	Successful - Qualification levels
		+ Sine	3	85 g - pk	(Z)	
GPS	1	Random	3	79 grms	(Y)	Successful Qualification Test
	38	Random	3	40 grms	(Y)	Successful Acceptance Tests as of 3-17-76
MJS	3	Random	3	154 grms	(X)	Successful - Qualification levels
		+ Sine	3	210 g - pk	(X)	
	14	Sine	3	141 g - pk	(X)	3 Failures: 2 blocked capillary tube 1 valve leak
	4	Sine	3	141 g - pk	(X)	Successful - All Pre-Vib Fired - February 1976

NOTES:

All qualification level tests were conducted on engines which had previously been acceptance fired.

3.0 DISCUSSION

3.1 Teardown of F/N 024 and 029

Figure 3-1 is a SEM photograph of the catalyst particles removed from the capillary tube of F/N 029. The largest particle dimension measured from this photograph is 0.0025 inch. Table 3-1 summarizes the measurements of the catalyst bed made following disassembly of both injector subassemblies. After removal of the catalyst, both injectors were microphotographed. Figure 3-2 shows both injector screens. Measurements from these photographs reveal the relative screen orientation to be 35° for F/N 029 and 45° for F/N 024. These figures demonstrate clearly the pattern of open holes between the two screens of each injector, an inherent geometrical occurrence. Since these screens are 100 mesh utilizing 0.004 inch diameter wire, the hole openings are 0.006 inch squares. When this geometrical pattern was first observed, it was recommended to orient the two screens "square-on-square", thereby eliminating all open holes. However, in addition to the impractibility of such an arrangement, a study of the three dimensional geometric effects reveals an equivalent open area with minimum dimensions on the order of 0.004 inch. Figure 3-2 b also shows a catalyst particle on the face of the injector with dimensions approximately the same as the wire.

Both injectors were potted in epoxy (EA 934) and sectioned to examine for delamination between the two screens. Figure 3-3 shows microphotographs of two sections on injector F/N 029. It has been estimated that there may be as much as 0.002 inch delamination between the two screens. However, this is extremely difficult to estimate in view of the three dimensional nature of the problem. Figure 3-4 is a similar section from F/N 024.

PARTICLES REMOVED FROM F/N 029 AT 1346X

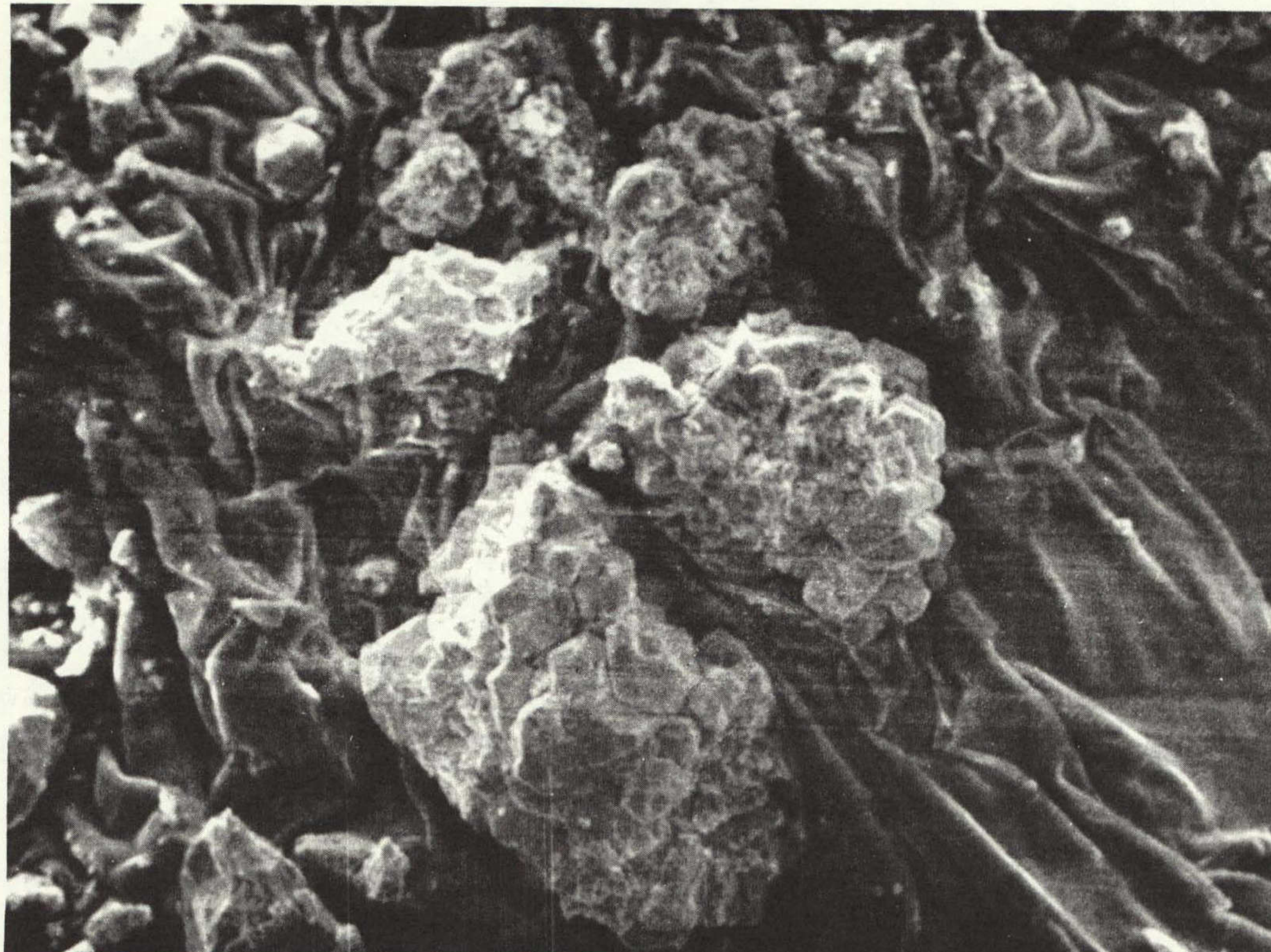

Figure 3-1

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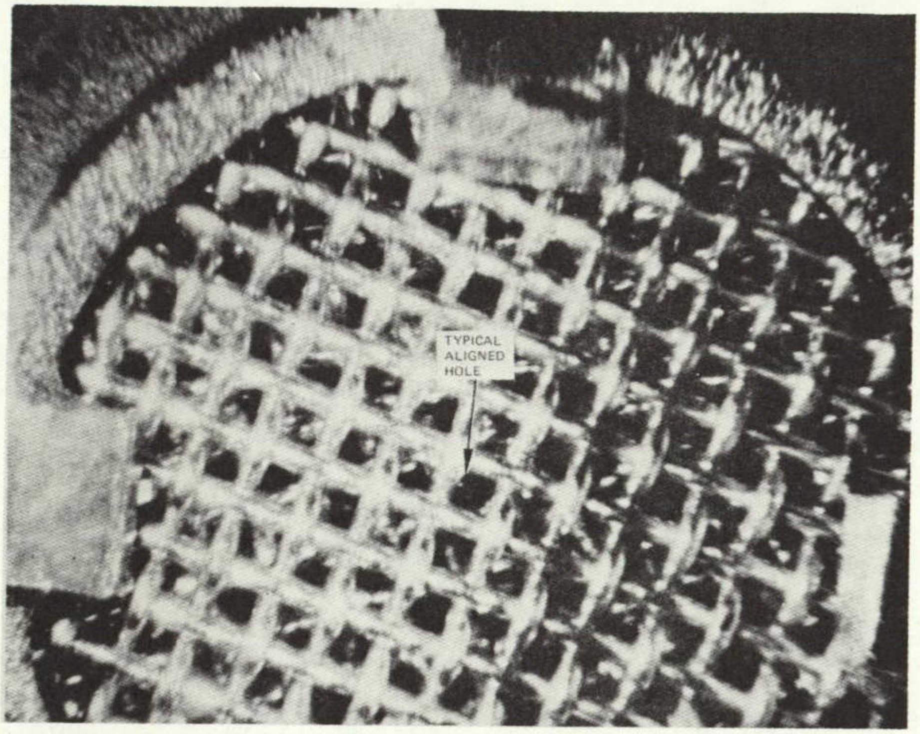
TABLE 3-1

F/N 024 & F/N 029 Teardown

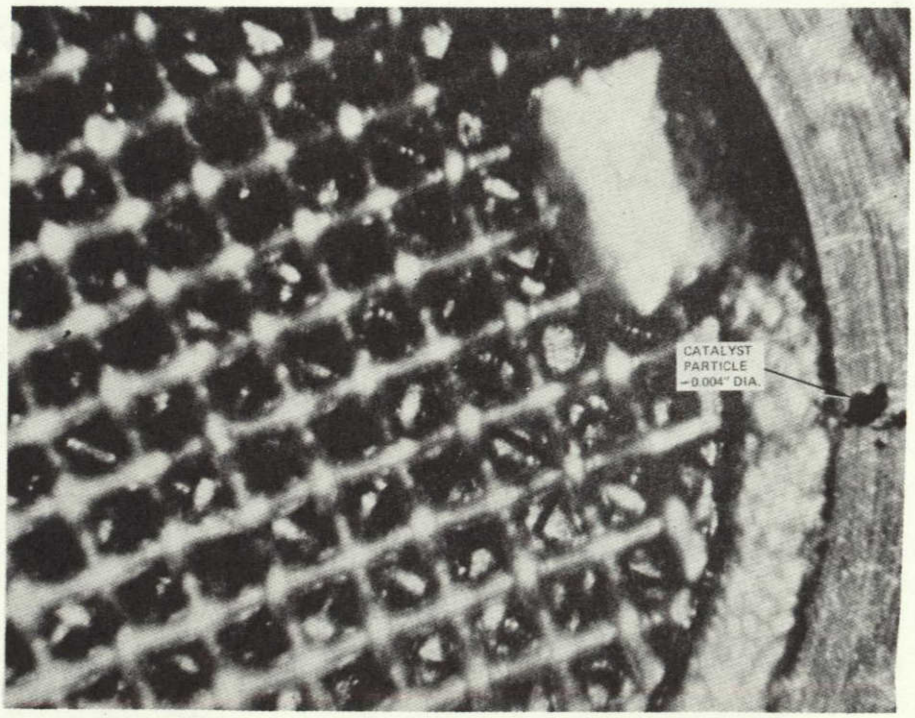
Catalyst Bed Examination

	F/N 029	F/N 024
Weight Loaded, grms	1.91	1.92
Weight Removed, grms	1.796	1.827
(Some lost on Disassembly)	(0.114)	(0.093)
Size Distribution:		
25-30 Mesh, grms	1.658	1.623
%	92.3%	88.8%
> 25 Mesh, grms	0.013	0.035
%	0.7%	1.9%
Fines, grms	0.125	0.169
%	6.9%	9.3%
Size Distribution of Fines:		
30-40 Mesh, %	69	71
40-50 Mesh, %	16	14
50-60 Mesh, %	5	3
> 60 Mesh, %	10	12

INJECTOR SCREENS FROM P/N 029 AND 024



a) INJECTOR SCREENS FROM F/N 029



b) INJECTOR SCREENS FROM F/N 024

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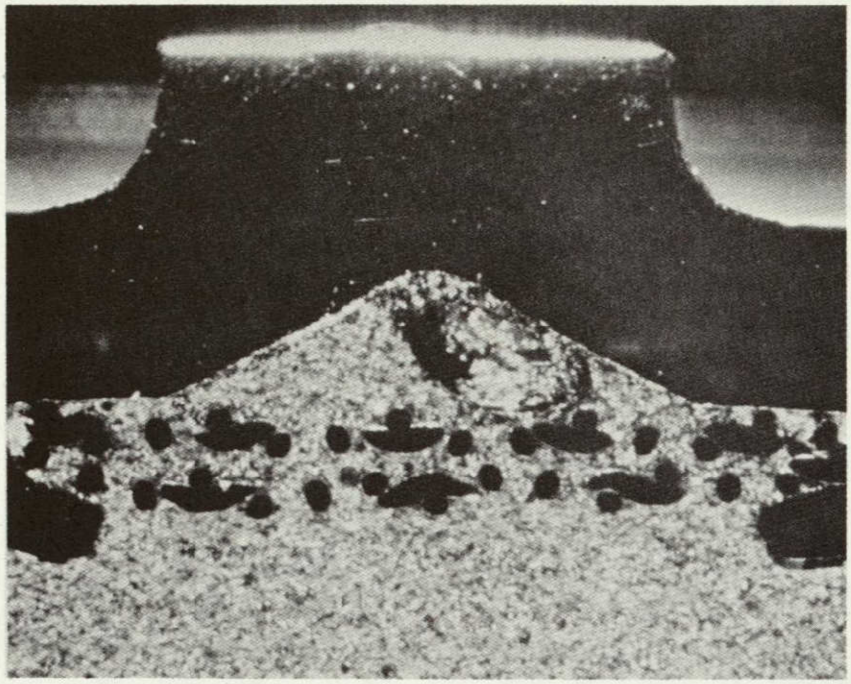
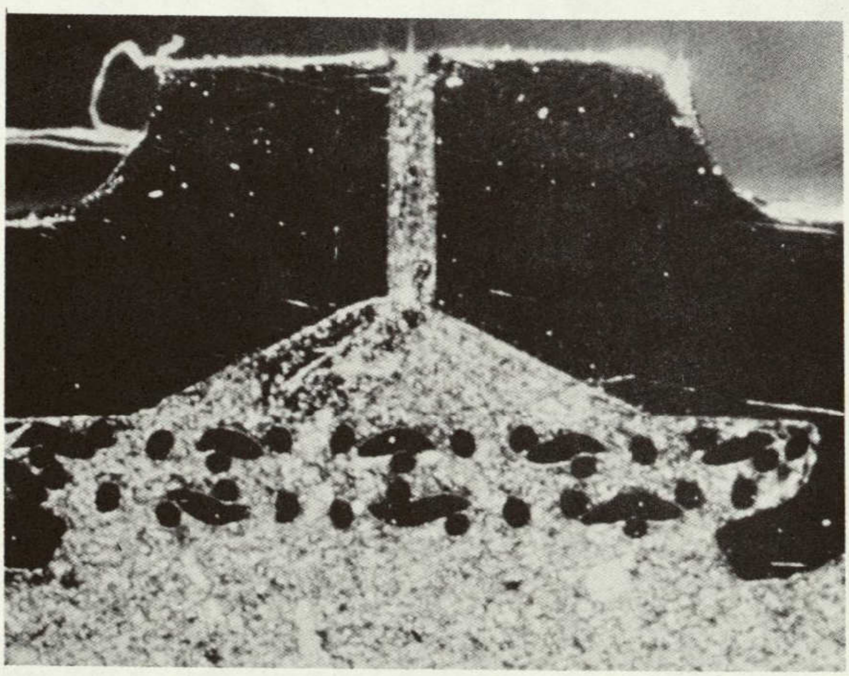
F/N 029 INJECTOR SECTION



a) FIRST SECTION



b) SECOND SECTION

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F/N 024 INJECTOR SECTION

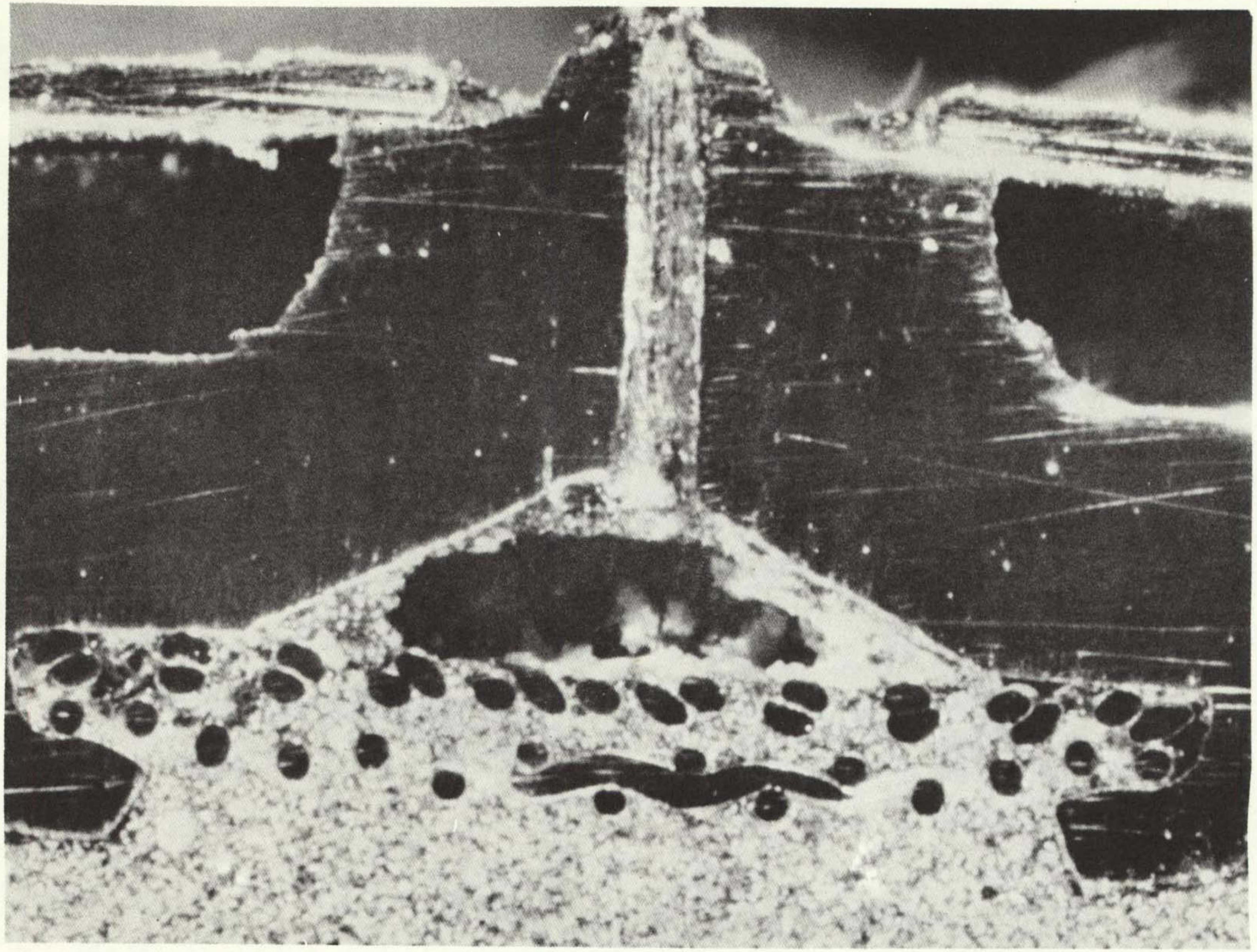

Figure 3-4

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As a result of this investigation, the emphasis of the special study program was placed on the design studies to provide an injector element which would preclude the transport of catalyst fines, and the packing studies to eliminate catalyst fines from the bed.

3.2 Capillary Tube Investigation

The failure analysis of both F/N 029 and 024 had isolated the capillary tube blockage to the first 90° bend upstream of the catalyst bed. In order to evaluate the internal characteristics of these tubes, a stock sweep was conducted to isolate minimum radius capillary tubes for further investigation. This stock sweep revealed one manufacturing lot of tubes as undersize on this particular radius (reference Figure 3-5). Three samples from this lot, together with three samples from an acceptable lot were forwarded to JPL for evaluation. An investigation into the utilization of this bad lot indicated all units built to date had the suspect tubes. As a part of the failure analysis on F/N 029 and 024, X-ray examination had been made of the plugged capillary tube. Subsequent measurements of this film confirmed less than print radii.

Dimensional inspection at JPL recorded the minimum radius from the unacceptable lot as 0.057 inch (drawing requirement 0.12 ± 0.03 inch), and a maximum radius on one part at 0.160 inch. Measurements of the ID were made via 12X examination of X-ray film of the suspect areas (Kodak type M-8, 100 KV at 5 ma for 30 seconds at 36 inches). A maximum ID reduction of 0.002 inch flattening was measured on the undersize radius. Additionally, examination of all bends to print, including the oversize radius, revealed 0.001 inch flattening. There were no apparent ID surface blemishes noted on any units.

Since the final injector assembly includes a thermal shunt brazed to the capillary tube immediately upstream of the catalyst bed, further investigation of this area was warranted. This portion of the tube from F/N 029 and 024 was sent to JPL for sectioning together with a residual capillary tube from the ATS Program. Sectioning and photomicrographs of these tubes confirmed clean ID surface finishes for all conditions, and showed an excellent braze with no internal effect at the thermal shunt.

DETAIL OF DRAWING CAPILLARY TUBE

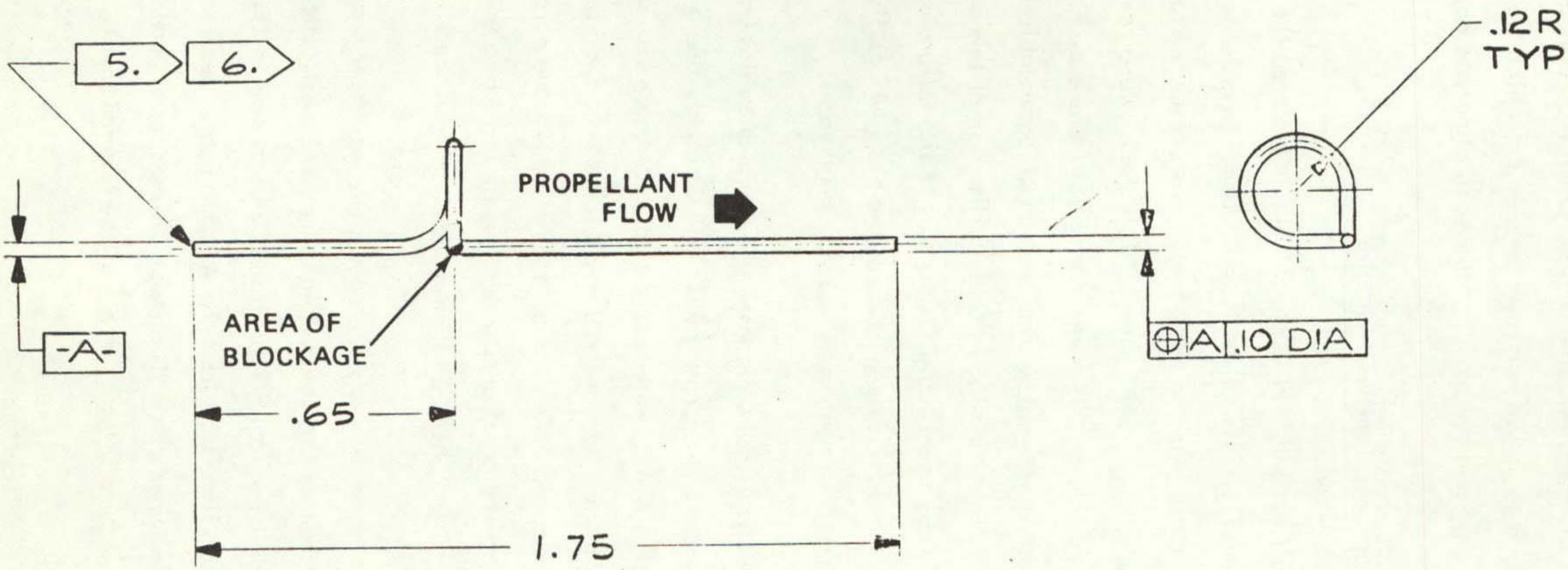


Figure 3-5

3.2.1 Forming Study

Isolation of the bad lot of capillary tubes necessitated a review of the form die. This review showed the form die (RRC tool number FB 27319-101) would maintain all drawing tolerances. The bad lot of tubes had either been fabricated without proper use of the tool or subsequently damaged in handling.

Concurrent with the foregoing JPL examinations, attempts were made to form tubes while a wire was held internally. This technique would assure no excessive crimping or flattening. Successful bends were achieved with 0.007, 0.008 and 0.009 inch wire. In all cases, the wire was removed successfully; however, with the 0.009 inch wire it was necessary to restrain the tube in the form die while removing the wire. The feasibility of this technique had been demonstrated. Questions were raised, however, regarding subsequent material compositions within the tube and definition of adequate final passivation. These questions, coupled with the determination of negligible flattening when formed to print, lead to the conclusion that changes to the forming process would not be necessary so long as drawing tolerances were maintained and continuously inspected through subsequent processing.

3.3 Design Studies

The design studies concentrated on three specific areas of concern relative to capillary tube plugging:

a) Dispersion Element
b) Dispersion Element Retention
c) Capillary Tube

Investigations into each of these areas are discussed herein.

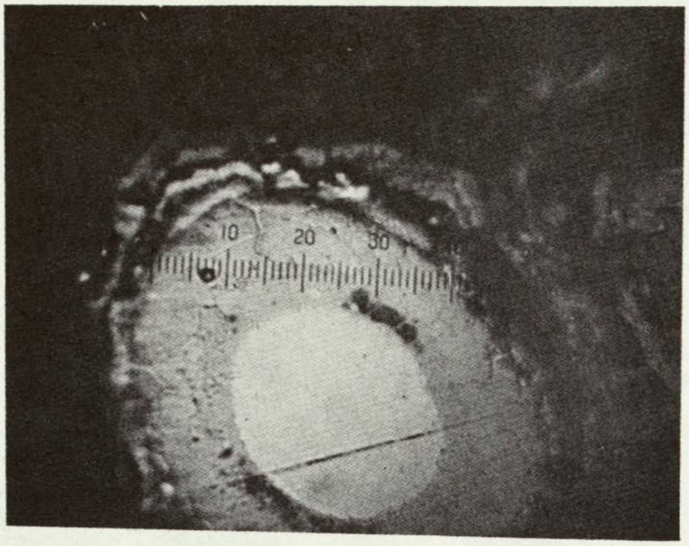
3.3.1 Dispersion Element

The baseline dispersion element design consists of two 100 mesh, Rhodium platted, Haynes 25 screens, oriented at 45° to each other. As discussed in Section 3.1, this orientation does not preclude the movement of fines as large as 0.006 inch upstream to the capillary tube. Although the majority of the openings are much less than this, there are a finite quantity (approximately 15%) at this dimension. Reorientation of the screens was studied but discarded after investigation of the three dimensional effects. The addition of a third screen was also evaluated but eliminated due to increased thermal mass and available catalyst migration paths. Fine mesh screen was considered as the most realistic change which might significantly reduce migration. However, all finer mesh screen utilizes smaller diameter wire, increasing the sensitivity to nitride damage. The Materials and Process Department was requested to evaluate the relative merits of candidate materials. The injector element from T/VA S/N 001, which had demonstrated margin life, was sectioned and microphotographed. Figure 3-6 presents two of these photographs showing extensive nitriding. The rhodium plating which is utilized to impede the nitride attack has become fragmented and ineffective. It is significant to note that this engine had flowed in excess of 156 lbm of propellant, well above specification requirements. However, a reduction in wire diameter with this material would significantly limit the life capability.

Figure 3-7 presents two microphotographs of platinum - 10% rhodium screen utilized in a 0.5 lbf REA for a similar life test. These pictures show no nitriding whatsoever, and prove applicability as an alternate material. The softness of the material is also apparent in these photos, with localized deformation, and must be considered in any application.

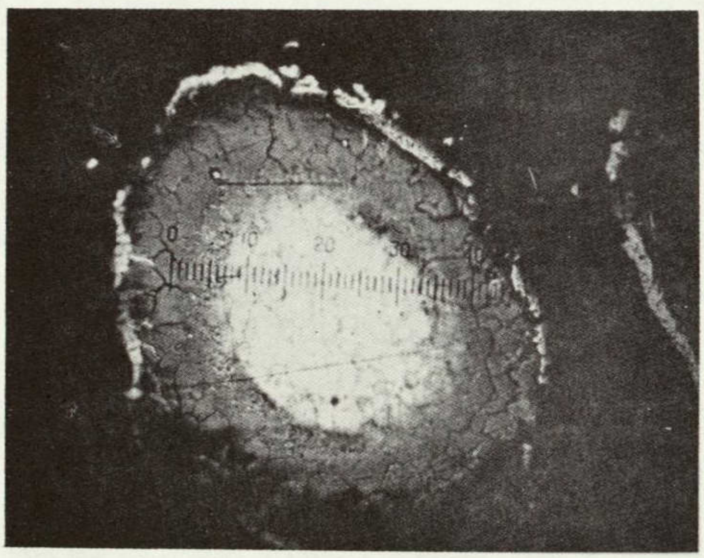
These results are in agreement with reference (1) which indicated superior nitriding resistance characteristics of platinum - 10% rhodium. Reference (1) also identified Nicrome V as an excellent candidate material. Procurement efforts for finer mesh filter materials were therefore concentrated on these two materials. Samples were obtained of these candidate materials and flow calibration tests conducted in a fixture simulating the injector. Materials tested included:

SECTION OF INJECTOR SCREEN S/N D01



UNETCHED D01 475X

a) DARK SURFACE INDICATES COMPLETE NITRIDING. LIGHT CORE MATERIAL UNNITRIDED.



GLVCEREGIA ETCH D01 475X

b) FRAGMENTED RHODIUM PLATING ON SURFACE. DARK AREA NITRIDING. CORE OF WIRE EMBRITTLED. RHODIUM DIFFUSION ALONG GRAIN BOUNDARY CAN BE OBSERVED AT LEFT EDGE AND AT TOP OF WIRE.

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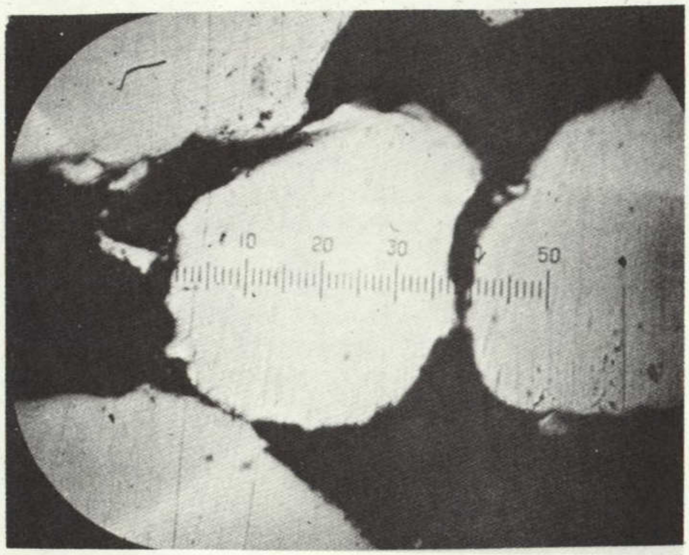
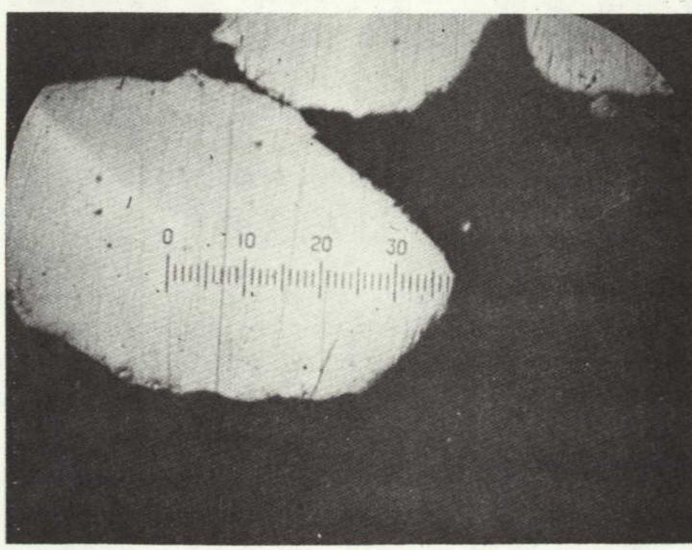
SECTION OF PI – 10% Rn SCREEN FROM 0.5-lbf REA



0.5 lbf 475X

a) PLATINUM SCREEN WIRE, NO EVIDENCE OF NITRIDING IRREGULAR SHAPE DUE TO CATALYST ATTRITION OF SOFT PLATINUM AND IN PART FROM MOUNTING GRINDING AND POLISHING



0.5 lbf 475X

b)

1) 50 x 250 mesh Driver Harris 242 (Nicrome V) - single layer

2) 50 x 250 mesh Driver Harris 242 - three layer

3) 50 x 250 mesh N155

4) 120 x 400 mesh Stainless Steel

5) K mesh (5μ rating) Nickel

6) 12 x 64 mesh Haynes 25 - two layer

These tests were made on individual test articles as well as various combination of these materials. Results indicated that all combinations had pressure drops equivalent to the baseline injector element. The susceptibility to contamination precluded the use of any filter element finer than the propellant valve inlet filter, which is rated at 10 microns nominal, 25 micron absolute. This constraint, combined the results of a procurement search for materials lead to the selection of 120 x 400 mesh Platinum - 10% Rhodium and 50 x 250 mesh Driver Harris 242 as the primary candidates for screen modification. A comparison of the heat capacity of the 120 x 400 mesh material with the baseline indicated a 38% decrease with a single layer or a 24% increase with a double layer. Since excellent thermal margin (insensitivity to boiling) has been demonstrated with the baseline design, there are no thermal concerns with a single layer of the new material.

3.3.2 Dispersion Element Retention

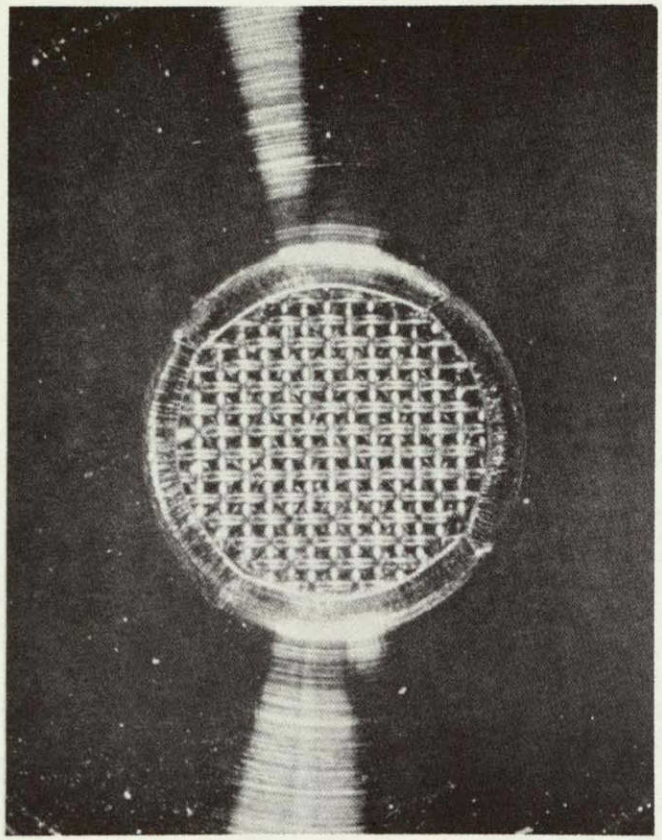
The baseline injector configuration employs four (4) tabs (0.030 inch wide, 0.020 inch long) to retain the element in the injector body. Since these tabs are bent over the screen, it was postulated that laterial movement of the screen may occur during this operating resulting in peripherial gaps or delamination between the two screens. The possibility of fine migration around the edges of the screen was further emphasized by a review of the detail drawings which permit a worst case diametral clearance of 0.015 inch. Stock sweep of the detail parts, however, revealed all screens had been stamped with the same die which was at maximum tolerance. Therefore the maximum diametral clearance was only 0.005 inches.

Many alternate weld and swage configurations were examined to provide 360 degree screen retention. Manufacturing feasibility studies were conducted and did successfully develop a swage preparation and tool design which resulted in the parts shown in Figure 3-8. These screen overlaps on these samples has been held to 0.010 to 0.015 inch. Although minimized, this does increase the stagnent propellant flow area and will have to undergo full development testing prior to implementation for flight.

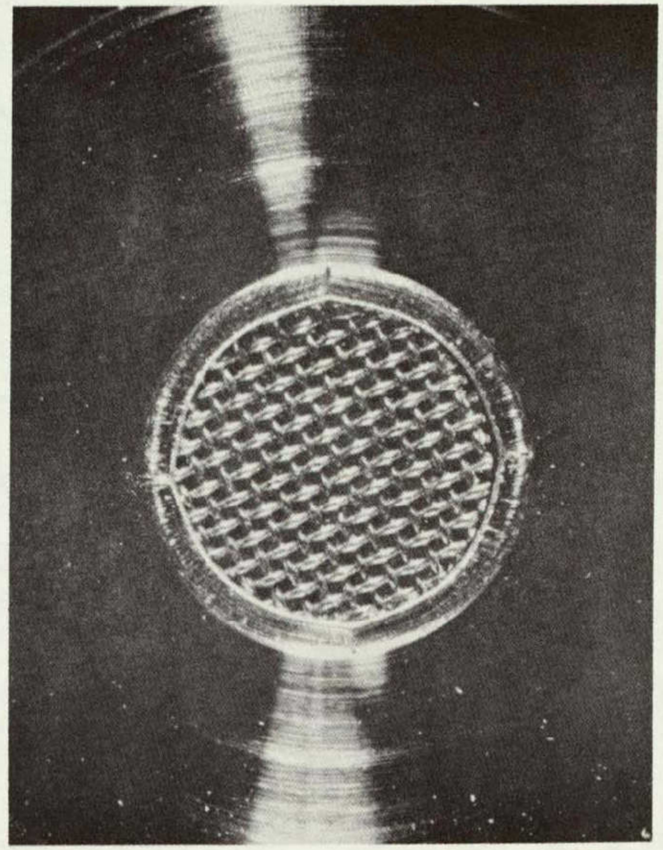
3.3.3 Capillary Tube

A special test series was designed to determine the sensitivity of the capillary tube to plugging. Originally, this series attempted to plug sample tubes with controlled sizes of catalyst fines. The test set up used is shown in Figure 3-9. For the first tests fines smaller than 325 mesh were introduced to the funnel and drawn through the tube via suction from the syringe. Catalyst suction was easily obtained. Plugging tests were accomplished by applying pressure from the syringe and monitoring the catalyst in the funnel for flow. These tests did not result in complete blockage with any of the sizes tested. To better simulate the actual conditions, the particles were moved by vibration. A vibropencil was held against the clamp holding the funnel. Partial plugging was obtained with 80 - 100 mesh fines in tubes with sharp 90° bends, however, this plug was readily cleared with a water flush. The syringe was then filled with water prior to moving catalyst into the capillary tube. After a small quantity of catalyst was vibrated into the tube, water pressure was applied from the syringe. In 90% of the cases, this technique resulted in a complete plug of the tube with all size ranges of fines.

Having established a test technique that simulated the blockage of F/N 029 and 024, 360º SWAGING TEST FINAL SAMPLES



4 – 0.010 IN. SLOTS



4 – 0.004 IN. SLOTS

Figure 3-8

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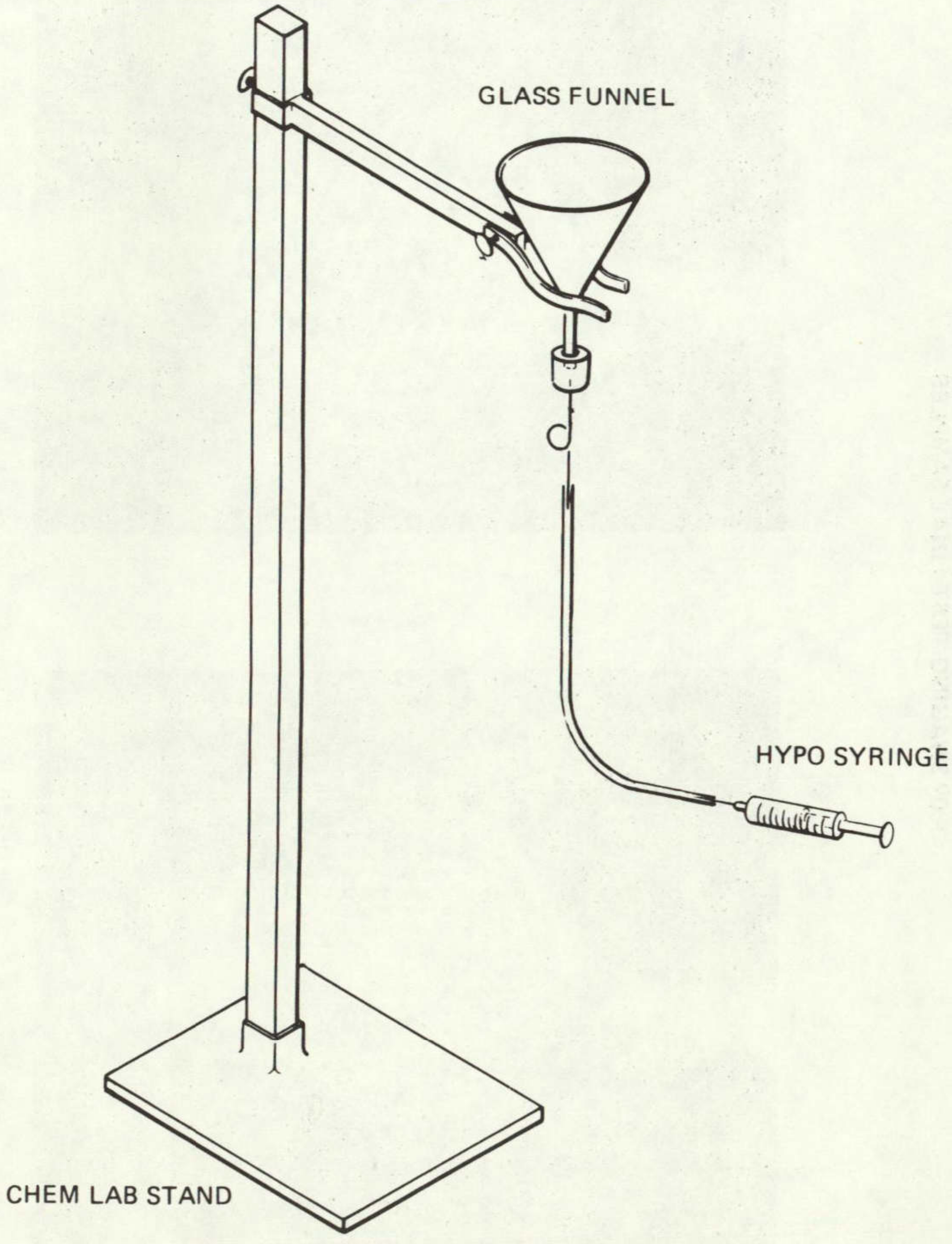
CAPILLARY TUBE PLUGGING STUDY TEST SETUP



the test was expanded to identify solutions. Glass capillary tube (ID = 0.0115) was formed into the baseline configuration and subjected to the same test sequence. To obtain complete blockage it was necessary to use fines greater than 100 mesh, however blockage would repeatedly occur at the identical location isolated on F/N 029 and 024. Alternate capillary tube shapes had been proposed to eliminate these 90° bends as shown on Figure 3-10. Glass tube tests with the in-plane helix, showed it to be just as sensitive as the baseline. With this configuration fines collected at the low point.

Additional tests with the normal capillary tubing with baseline design (to print and with sharp radius 90° bends) and the corkscrew configuration indicated no improvements in plugging tendancy. The sine shape tube was not tested due to analytical predictions (confirmed by previous test) of bending fatigue failure at a restrained end due to mechanical loads imposed by thermal cycling. Similarly a straight tube was not evaluated in view of the predicted 130 ksi tensile stress due to 0.004 inch differential thermal growth.

A special series of tests were conducted to determine the quantity of fines required to cause complete blockage in the baseline design. In no case could blockage be obtained with less than 1 mg of catalyst. A series of measurements of these fines for particle mass as a function of size is presented in Table 3-2, showing 3000 particles at approximately 0.010 inch diameter are required to obtain this one milligram.

3.4 Catalyst Strength Study

A survey of build records for the 0.2-lbf T/VA's is summarized on Table 3-3. Since no capillary tube plugging had been observed on the breadboard T/VA's which had utilized a different batch of catalyst than the flight T/VA's, the catalyst records were reviewed. Table 3-4 presents the catalyst strength data for all catalyst used in this thrust range. This data is obtained from a mechanical crush test conducted on

ALTERNATE CAPILLARY TUBE CONFIGURATIONS

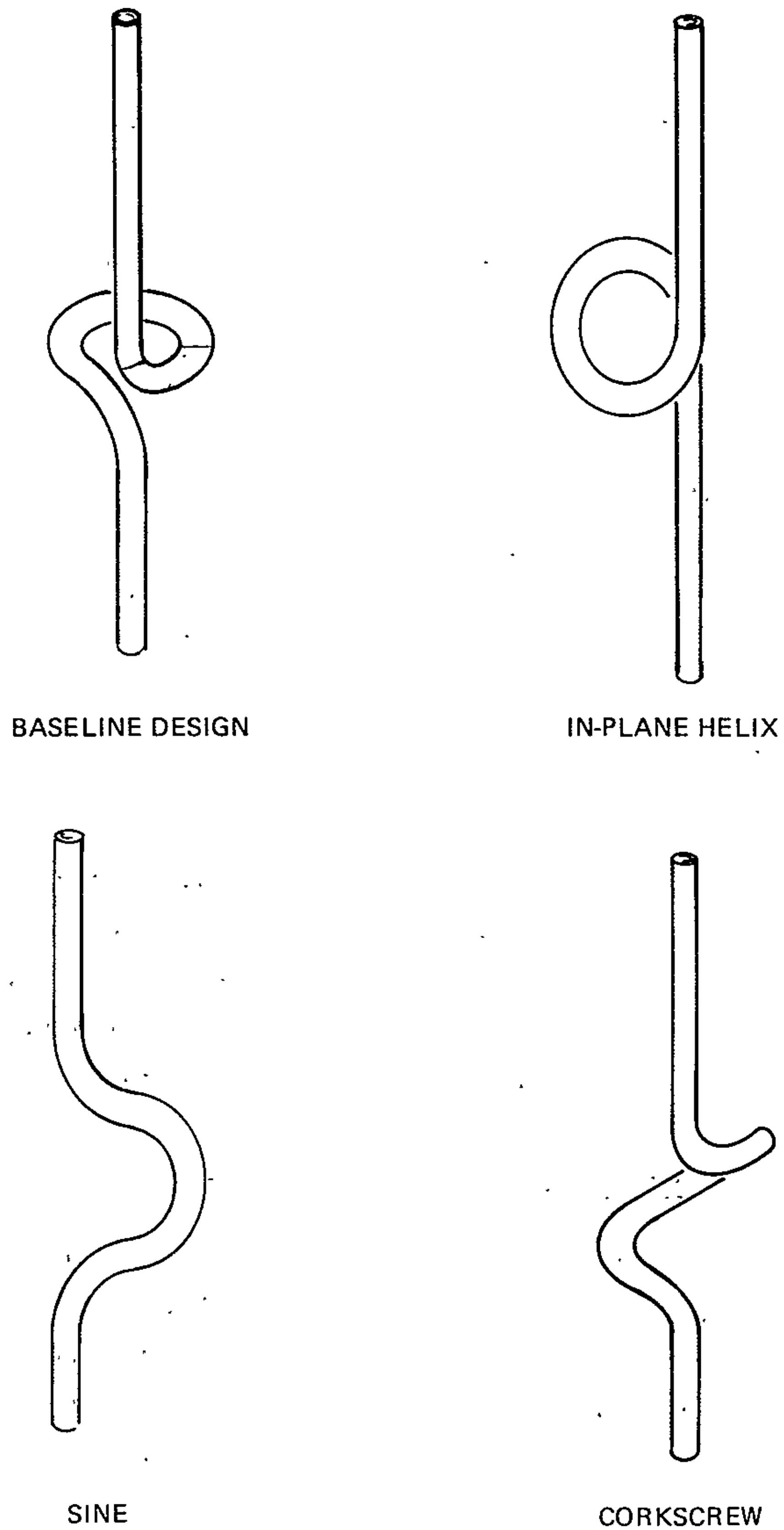


 Figure 3-10

TABLE 3-2

PARTICLE MASS

Mesh Size (Inches)	Mg/Particle	# To Get/Mg
30 - 40 (.0234 - .0165)	0.3	3
40 - 50 (.0165 - .0117)	0.07	14
50 - 60 (.0117 - .0098)	0.004	250
~ 60 (~.010)	0.00033	3000

TABLE 3-3

BULID RECORDS 0.2-LBF T/VA'S

Serial Number	Factory Number	Catalyst Lot No.	Operator	Weight Loaded gms	Remarks
B01	001	44814	1789	1.94	
B02	005	"	"	1.90	
B03	006	"	"	1.91	
B04	007	"	"	1.93	
B05	003	"	"	1.91	
B06	009	"	"	1.92	
B07	010	"	"	1.91	
B08	011	"	"	1.92	
B09	012	"	"	1.91	
-	008	"	"	1.86	Plugged Throat
B10	008R	31111	1789	1.92	
013	045	45489	1571	1.89	Qualification Unit #2
014	022	"	8088	1.89	
015	030	"	"	1.89	
-	024	"	"	1.89	Plugged Cap Tube
016	032	"	"	1.87	
017	033	"	"	1.88	
018	023	"	"	1.96	
019	028	"	"	1.88	
-	029	"	7431	1.91	Plugged Cap Tube
020	021	"	7431	1.92	
021	027	"	7431	1.92	
022	026	"	8088	1.88	
023	020	"	7431	1.89	
024	025	"	6163	1.85	

TABLE 3-4

CATALYST STRENGTH DATA SUMMARY

LOT NO.	USED ON	PARAMETER . . . . DEFLECTION ACC CRITERIA. . . ($\leq$ 0.100)	RECOVERY ($\geq$ 0.015)	REMAINING ($\geq$ 75%)
44814	B/B T/VA	0.0716	0.0263	82.5
45489	FLT T/VA (Tested as Lot 45308, 4/1/75)	0.0975	0.0252	85.0
	From 38459 Viking Mix of Six (6) Batches	0.0602 $\pm$ 0.0185	0.0187 $\pm$ 0.0041	84.6 $\pm$ 4.8
	37454 - Original Data Repeat Test 2/13/76	0.0753	0.0205	79.4
45257	GPS (Tested as Lot 45490, 4/1/75)	0.0758	0.0219	89.8
	From 32467 Viking Mix of 46 Batches - Original Data	0.0728 $\pm$ 0.0285	0.0245 $\pm$ 0.0057	83.8 $\pm$ 9.0
29578	ATS F&G	0.090	0.028	80.0
42420	SATCOM	0.066	0.022	88.3

3.4 (Continued)

a 6.0 grm sample from each shrinkage lot (nominally 300 grms). The retest data on the flight lot of catalyst did indicate a very high deflection (just within acceptance limits), consequently a fresh sample from this lot was tested for verification. The results, as shown on Table 3-4, indicate this catalyst to be within the normal family.

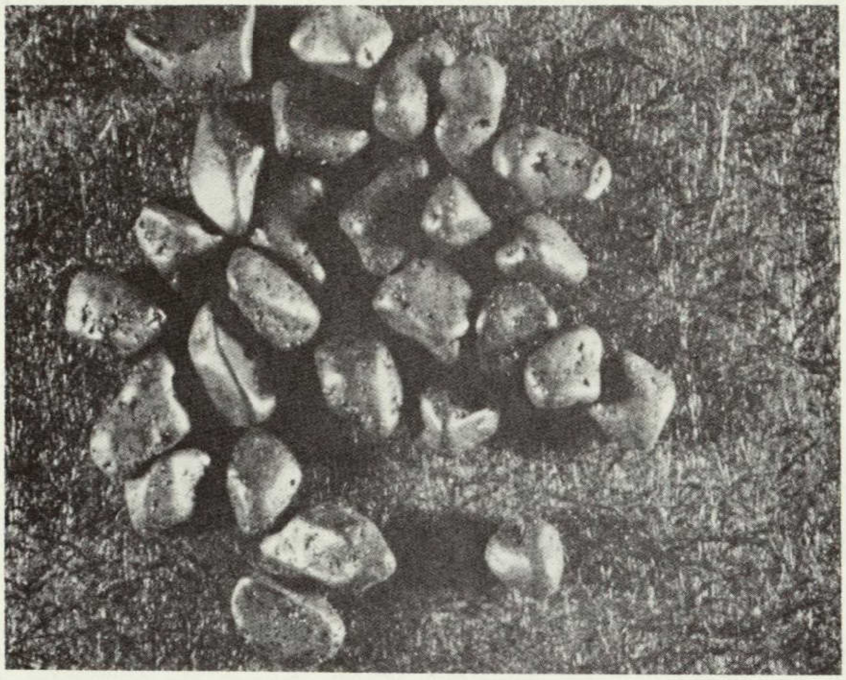
Since catalyst fines and particles were suspected of causing problems with the 0.2 lbf MJS engines, catalyst from the same lot used in the engines was investigated to determine if the problems were attributable to the catalyst per se rather than to its treatment during packing and vibrating engines. Catalyst from RRC Lot 45489 was used. This lot was taken from RRC Lot 38459 which in turn was derived from RRC Lot 37454-1 through -6. This was catalyst remaining from the Viking program.

Initially, microscopic examination was made in an effort to segregate so-called "flat" particles from so-called "normal" particles since a subjective opinion had been made that the catalyst used to pack the engines had numerous particles that seemed to be flatter than the remainder of the catalyst granules.

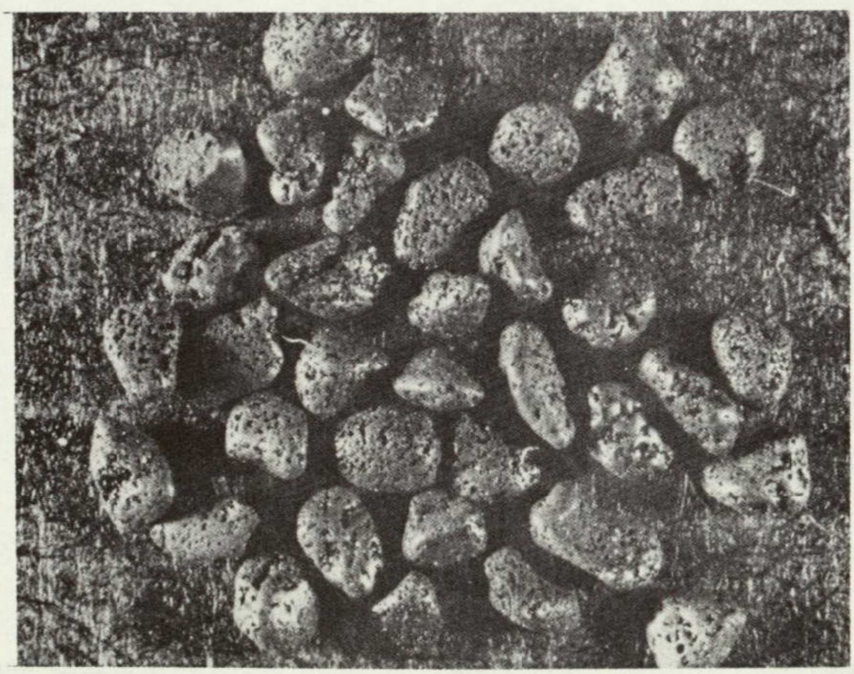
Examination of 107 grains was made and 21 (19.6%) were judged to be flat. However, there was no great degree of distinction from the remaining particles. A second portion consisting of 422 granules was examined and only 15 (3.6%) were judged to be "flat". None of this effort seemed to result in any meaningful distinction, there were no distinctly "flat" particles.

During microscopic examination of the catalyst granules while looking for "flat" granules, a difference in the surface character was noted as shown in Figure 3-11. Some granules had many cavities while others were smooth. A number of granules were segregated and used for crush tests. The results of the crush tests are tabulated in Tables 3-5 through 3-7. They show that for catalyst granules selected at random (Table 3-5), a wide range of crush strength was experienced. For selected catalyst granules of the "hard" or "soft" category, it appeared that "soft" granules

"HARD" VERSUS "SOFT" CATALYST FROM LOT NO. 45489



(a) "HARD" CATALYST



(b) "SOFT" CATALYST

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3.4 (Continued)

could be distinguished from hard rather imperfectly (see Tables 3-6 and 3-7). The "soft" category contained granules with low crush strength but also contained granules with high crush strength. The "hard" granules had a wide range of crush strength values, but did not contain those with very low values, i.e., not the "soft" granules. Testing of five "flat" granules showed that all had high crush strengths.

The crush test fixture used was improvised since no apparatus was available for crushing single granules. It consisted of a rod with a flat face (to serve as an anvil) attached to a rack and pinion gear which allowed the anvil to be lowered onto a catalyst granules and then to exert an increasing force until the granule is crushed. The force exerted was measured by using a top loading balance as the platform as well as the measuring device. Some granules were cracked prior to crushing, others remained intact until their crush strength was exceeded whence they exploded into fine particles and dust, yet other granules crumbled to small particles in a much slower and less forceful manner. A wide scattering of crush strength values was recorded some granules being crushed with 50 grams force while others required 500-600 grams, occasionally even more.

A review of this work led to the abandonment of sorting catalyst to obtain "flat" granules since there did not seem to be any really flat granules. A further testing of the possibility of sorting granules into "hard" and "soft" categories was carried out. As the data in Tables 3-6 and 3-7 shows, granules that were selected as "hard" contained few "soft" granules. "Soft" granules did contain numerous soft granules, i.e. low crush strength, but this category also contained many strong, i.e. "hard" granules as well.

Over 8 grams of 25-30 mesh Shell 405 catalyst were separated into "hard" and "soft" groupings. The "hard" granules were then used to pack 0.2 lbf MJS engines for further tests. Details of these tests are presented in Section 3.5. After the packing tests were concluded, the catalyst was removed and recombined. The combined catalyst was then sieved and a six gram sample was

TABLE 3-5

PARTICLE CRUSH TEST DATA

One vial of Shell 405, 25-30 mesh catalyst lot 45489 was used to determine the following data (Lot 45489 was derived from Lot 38459 which in turn was made by combining Lots 37454-1 through -6). One hundred and seven grams of catalyst were taken from the vial and sorted into two categories, "normal" and "flat". Eighty-six grains were found to be "normal" and 21 were "flat" or 19.6% "flat". A second portion was sorted (422) and 15 were classed as "flat" or 3.6%. The following crush data were obtained using the apparatus described in the text.

Grain #	Force, g	Grain #	F, g	Grain #	F, g	Grain #	F, g
1	230	20	131	39	303	58	120F
2	75	21	191	40	109	59	285P (179
3	207	22	60	41	52	60	323P
4	79	23	324	42	62	61	249P
5	255 (198)	24	229	43	167	62	439P (128
6	193 (149) (136)	25	369	44	521	63	441P (235
7	167	26	92	45	303	64	288P
8	422	27	123	46	278	65	126P
9	77	28	228 (169)	47	262	66	299P
10	333	29	249	48	281	67	315P
11	201	30	228	49	403	68	194P
12	317	31	203	50	297	69	645P
13	230	32	195	51	150	70	827P (179
14	143	33	154	52	680 (362) (152)	71	315P (97)F
15	163	34	254	53	783	72	230P
16	66	35	90	54	226P		
17	250 (140)	36	55	55	235P		
18	175	37	210	56	164F		
19	111	38	225	57	649P (290)F		

Grains 1-32 were selected at random
Grains 33-45 were selected as being "soft"
Grains 46-67 were selected as being "hard"
Grains 68-72 were selected as being "flat"
Figures in ( ) were values of force where grains cracked or fractured F
P after a value means the sample was pulverized

TABLE 3-6

CRUSH STRENGTH OF "HARD" CATALYST GRAINS

A crush test was done on individual grains of lot 37454-6 (the "mother" lot of lot 45489) which had survived intact the crush test done on six grams as part of the normal catalyst testing after shrinkage (see RRC PS-0060 and RRC TP-0095).

Grain #	Force, g
1	249
2	160
3	216
4	834 (696)
5	436
6	302
7	309
8	198
9	368
10	828
11	530
12	345
13	636
14	660
15	581
16	632
17	459 (300)
18	304
19	330
20	243
21	859
22	271
23	420
24	837
25	263
26	320 (204)
27	208
28	413
29	306 (182)
30	248
31	232
32	202
33	310
34	569 (196)
35	428 (272)
36	353 (157)
37	279 (71)
38	653
39	48

All 39 grains were selected as being "hard" after microscopic examination at 30X magnification.

Grains 12-38 were photographed at approximately 11.5 X magnification.

These 39 grains were from an initial batch of 988 grains which were sorted into 763 "hard" and 225 "soft" grains. See Table 3-7 for values on soft grains.

Values in ( ) represent forces at which grains cracked.

TABLE 3-7

CRUSH STRENGTH OF "SOFT" CATALYST GRAINS

Grain #	Force, g
1	230 (62)
2	138
3	73
4	135
5	64
6	220
7	209 (117)
8	68
9	67
10	115
11	197
12	143
13	113
14	79
15	49
16	162
17	181
18	68
19	55
20	47
21	119
22	149
23	88
24	91
25	132 (96)
26	77
27	143
28	167
29	467
30	67
31	132 (68)
32	345
33	198
34	143
35	616 (394) (116)
36	273 (202)

All 36 grains were selected as being "soft" after microscopic examination at 30 X magnification.

Grains were photographed at 11.5 X magnification to show the pitted surfaces.

3.4 (Continued)

subjected to the regular crush test (documented in RRC TP-0095). The results were quite normal and did not suggest that the selected "hard" granules differed from catalyst selected at random. A comparison with the six original catalyst shrink batches from which this catalyst was derived shows no significant differences:

RRC Lot No.	Deflection	Recovery	% Survival
37454-1	0.063	0.019	85.0
37454-2	0.051	0.020	83.5
37454-3	0.062	0.017	83.0
37454-4	0.060	0.017	83.9
37454-5	0.069	0.020	84.7
37454-6	0.056	0.019	87.5
Average	0.060	0.019	84.6
45489 "Hard" granules	0.085	0.021	81.6

The effects of sieving Shell 405 catalyst granules were determined for a 2.5 gram portion from RRC Lot 45489. Three inch diameter stainless stell sieves were used (U.S. series 25, 30, 35, 40 and 45 sieves with pan and lid). The catalyst was placed on the U.S. 25 mesh sieve and the nest of sieves was placed on a "toothmaster" dental vibration at the "low" setting. (A Model 6-H Toothmaster vibrator manufactured by the Toothmaster Company, Racine, Wis., was used.) The sieves were vibrated for a total of twenty minutes, but vibration was interrupted periodically to measure the weight loss of the catalyst. The data in Table 3-8 shows that the weight loss ceased after fifteen minutes of vibration. The fact that only 1 mg of catalyst fines smaller than 45 mesh was generated showed that it was attrition that generated the fines rather than massive fracture or crushing of granules. Most of the weight loss was due to large particles which were in the range of 30-45 mesh. Based on this sample, it would appear that prolonged sieving under mild conditions is not an effective way to separate hard and soft granules.

A sample of 152 granules from the catalyst used in this sieving study was sorted into "hard" and "soft" granules and crush strengths were determined.* Thirty-eight of the granules were designated

*These results are presented in Table 3-9.

TABLE 3-8

EFFECTS OF SIEVING ON 25-30 MESH SHELL 405 CATALYST

STARTING WT. 2.514 g SHELL 405, RRC LOT 45489

Total Wt. Loss Grams	Total Time		Total % Wt. Loss	Total Wt. Loss g/min
0.041	15 sec (hand)		1.63	.164 g
0.068	15 sec (vibrator)		2.70	.108 g
0.091	30 sec	"	3.62	.092 g
0.101	45 sec	"	4.02	.040 g
0.105	60 sec	"	4.18	.016 g
0.107	75 sec	"	4.26	.008 g
0.108	90 sec	"	4.29	.004 g
0.115	105 sec	"	4.57	.028 g
0.122	120 sec	"	4.85	.028 g
0.126	135 sec	"	5.01	.016 g
0.127	150 sec	"	5.05	.004 g
0.131	165 sec	"	5.21	.016 g
0.136	180 sec	"	5.41	.020 g
0.140	195 sec	"	5.57	.016 g
0.153	6 min	"	6.08	.004 g
0.158	10 min	"	6.28	.0012 g
0.161	15 min	"	6.40	.0006 g
0.161	20 min	"	6.40	0

There was 1 mg of fines smaller than 45 mesh generated in this test. After 20 minutes total time at "low" setting on the vibrator the following distribution was found:

Mesh Size	Wt.
Larger than 25 mesh	0.037 g
25-30	2.353 g
30-35	0.189 g
35-40	1 mg
40-45	0.5 mg
Smaller than 45 mesh	1 mg
Total Wt.	2.5815 g

The difference between the total wt and the starting wt is moisutre gain (0.0675 g) or 2.7%.

TABLE 3-9

CRUSH TEST OF PARTICLES AFTER TWENTY MINUTES VIBRATION

Grain	Force, g	Grain	Force, g	Grain	Force, g	Grain	Force, g	Grain	Force, g
1	16	33	110	65	247	97	364 (107)	129	317
2	136	34	162	66	L	98	198	130	149
3	238	35	198	67	448	99	68	131	141
4	170 (111)	36	195	68	235	100	?L	132	159
5	96	37	200	69	210	101	367	133	435
6	134 (20)	38	132	70	283	102	283	134	L
7	152	39	187	71	223	103	371	135	484 (328)
8	85	40	520 (339)	72	321	104	830 (40)	136	244
9	82	41	160	73	70	105	524 (298)	137	495 (403)
10	94	42	207	74	290 (234)	106	346 (151)	138	263
11	67	43	215	75	148	107	273	139	253
12	102	44	120	76	340	108	318	140	429
13	L	45	101	77	513	109	189	141	220 (136)
14	292	46	500	78	80	110	172	142	651
15	180	47	130	79	270 (234)	111	259 (149)	143	107
16	228	48	347 (138)	80	630	112	280 (177)	144	408 (321)
17	216	49	282	81	135	113	200	145	377
18		50	198	82	275	114	264	146	385 (30)
19	442	51	143	83	344 (287)	115	L	147	276
20	264	52	296	84	596	116	524 (92)	148	238
21	250	53	120	85	302 (202)	117	168	149	133
22	243	54	292	86	215	118	214 (145)	150	L
23	313	55	156	87	321	119	233	151	L
24	136	56	115	88	550	120	209		
25	288	57	197	89	20	121	220		
26	248	58	162	90	684	122	184		
27	356	59	392	91	42 (20)	123	874 (510)		
28	227	60	108	92	383	124	408		
29	297	61	369	93	190	125	275 (208)		
30	248	62	302	94	255	126	343		
31	340	63	176	95	L	127	578 (546)		
32	334	64	144	96	169	128	447		

Grains 1-38 were classified as soft
Grains 39-151 were classified as hard
Values in ( ) represent force at which grains cracked
L represents grains lost in transferring from vial to crush apparatus

3.4 (Continued)

as "soft", several were exceedingly fragile and more or less exploded into dust with the application of only a few grams force. The phenomenon of granules exploding into dust is not unique to extra soft granules, however, since some of the strongest granules also undergo the same reaction when their crush strength is exceeded. However, the fact that such soft granules survived the sieving test confirms that gentle sieving is not effective in removing soft catalyst granules.

Since hand sorting of catalyst is exceedingly slow as well as tedious, attempts were made to classify the granules by use of a counter-current water separator. It was thought that the "soft" granules might have a lower density and thus be separable from the "hard" granules. A preliminary effort was made in which several grams of catalyst were placed in a glass tube (5/8 in. I.D. X 48 in. long) with a stainless steel screen insert near the bottom. An inlet tube through a rubber stopper (used to plug the tube) was connected to a centrigugal pump. The pump was fed from a 4 liter beaker of distilled water in which the glass tube was positioned so that the distilled water running out of the top of the tube cascaded back into the beaker. By adjusting the flow of water into the tube it was possible to suspend the catalyst particles. The same effect was possible by dropping catalyst into the top of the tube with a low flow of water and then increasing the flow to keep the particles suspended. When the flow was properly adjusted, some catalyst particles were carried out of the tube while others remained. Testing of the crush strength of the first run of catalyst separated, indicated the weaker strength granules were removed. However, repeated attempts to verify this preliminary data were not successful. Since the apparatus was very cumbersome to use, further testing was carried out with a modified apparatus. These results, showed that a separation of catalyst into hard and soft granules by this process was not possible.

Reference (2) describes an extensive series of investigations underway on causes of Shell 405 catalyst breakup. However, none of the catalyst used in this study has undergone the shrinkage treatment to which the MJS catalyst was subjected so the results are not directly applicable. It was pointed out, however, that improvement in the catalyst carrier and the catalyst itself were needed to remove the softer particles.

3.5 Packing Study

In April 1975 during acceptance test firings of breadboard T/VA's excessive chamber pressure spikes and annomalous engine behaviour was noted on T/VA F/N 008. At about this same time period the Momentum Wheel Desaturation Tests were terminated on development T/VA S/N D02 due to similar performance. Failure analysis of both units revealed catalyst particles had migrated through the slotted bed plate and were plugging the nozzle throat. The corrective action for this failure mechanism involved redesign of the bed plate from 10 - 0.012 wide slots to 20 - 0.006 wide slots. This change maintained the same flow area while significantly re-deducing the maximum particle size which could migrate through the bed plate.

Concurrent with this change, a packing study was instituted in an attempt to improve the engine roughness characteristics. The baseline packing procedure had been that evolved from the ATS 0.1 lbf program and used throughout the SATCOM 0.1 lbf REA program. Using one injector body and packing it with this procedure four (4) separate times an average weight of catalyst load of 1.89 grms was obtained with an average of 4.15% fines measured after packing. A series of tests with this same injector employing controlled vibration during packing and evaluation of the concept of "wet" packing did not improve either the packing density nor decrease the amount of fines. However, by increasing the tamping time after final top off, increasing the overpack from 0.005 - 0.007 to 0.008 - 0.010, and controlling the torque to the packing fixture to 1.5 in lbf, seven (7) successive packs on this same injector resulted in an average catalyst load of 2.01 grms and 2.49% fines measured after packing. This procedure together with the revised bed plate was used on breadboard T/VA S/N B10 and all flight T/VA's through February 1976.

3.5.1 Unwelded Nozzle Tests

With the institution of the special studies, a reverification of these foregoing results was planned. This test would employ multiple injector bodies and personnel as well as fresh catalyst ready for flight packing. Five injector bodies were packed by this procedure and resulted in an average load of 1.89 grms with 4.7% fines measured after packing. In each case, after removing the catalyst from the injector body, a cleanliness check was made of the injector assembly. Particle counts of these checks and the packing data revealed one operator, of the three used, to have

3.5.1 (Continued)

produced significantly more fines. Review of this operator's technique showed much less presieve time on the catalyst. The specific operation stated ". . gently sieve the catalyst . . ", for this operator this amounted to 5 or 10 seconds as opposed to 15 to 20 seconds for the others. Additional packs were conducted with varying presieve time as shown on Table 3-10. It is clear from this table that increased presieve time is required to reduce the available fines. Figure 3-12 summarizes all data collected on the fines generated by sieving (including that discussed in Section 3.4). The excessive fines produced by engineers' hand sieve provided further motivation to automate the operation and eliminate personnel variables. Consequently a mechanical sieve has now been baselined with 300 sec time required.

The use of torque to control axial force was questioned during the Special Study Coordination meetings. Consequently, a spot weld force gage was employed to determine the axial force applied by the packing fixture at the specified torque. Measurements on one of the three fixtures ranged from 62 to 79 lbf which corresponds to a catalyst pressure of 500 to 600 psi. This conflicts with the recommendations of references (2) and (3), of approximately 200 psi maximum. Subsequent measurements on the other two fixtures gave values as low as 20 lbf (159 psi), with very poor repeatability. It was therefore recommended that the packing fixtures be revised to incorporate axial force measurements and the force should be limited to 22 $\pm$ 3 lbf.

Additional tests with the "hard" catalyst segregated by the Chemistry Department (reference Section 3.4), and a controlled load fixture are summarized on Table 3-11. This data, combined with that of the catalyst strength studies concluded the effort on "hard" catalyst.

TABLE 3-10

PACKING STUDY RESULTS

Date/Description	Number of Packs	Number of Injectors	Presieve Time, Sec	Load Grms	Fines Incl. 30 Mesh Ret. Grms	Fines Incl. 30 Mesh Ret. %	Fines Excl. 30 Mesh Ret. Grms	Fines Excl. 30 Mesh Ret. %
5/75 SATCOM Baseline	4	1	?	1.89	?	?	0.08	4.2
5/75 Revised MJS Baseline	7	1	?	2.01	?	?	0.05	2.5
2/76 MJS Baseline	1	1	5-10	1.89	0.16	8.5	0.08	4.3
2/76 MJS Baseline	4	4	15-20	1.90	0.07	3.7	0.05	2.6
2/76 MJS Baseline	1	1	40	1.86	0.04	2.2	0.02	1.1
2/76 MJS Baseline	2	2	300	1.89	0.04	2.1	0.02	1.1

POST PACK INJECTOR FLUSH RESULTS

Presieve Time, Sec	Number of Samples	Number of Particles in Size Range 0.001"-0.002"	0.002"-0.004"	0.004"-0.005"	7.005"
5-10	1	60	11	1	5
15-20	4	23	4	1	3
40	1	6	1	0	0
300	2	18	3	0	0

FINE DISTRIBUTION RESULTS

	(Equivalent Microns) Inches	F/N 029	F/N 024	Pack Study By Presieve Time 5-10 Sec	15-20 Sec	40 Sec	300 Sec
30-40 Mesh	(600-400) .0234-.0165	69%	71%	89%	71%	75%	87%
40-50 Mesh	(400-300) .0165-.0117	16%	14%	6%	12%	13%	10%
50-60 Mesh	(300-250) .0117-.0098	5%	3%	2%	7%	6%	3%
∠ 60 Mesh	(< 250) .0098	10%	12%	3%	10%	6%	0%

11100-41

WEIGHT OF FINES VERSUS SIEVE TIME (SAMPLE SIZE, 2.5 GRAMS)

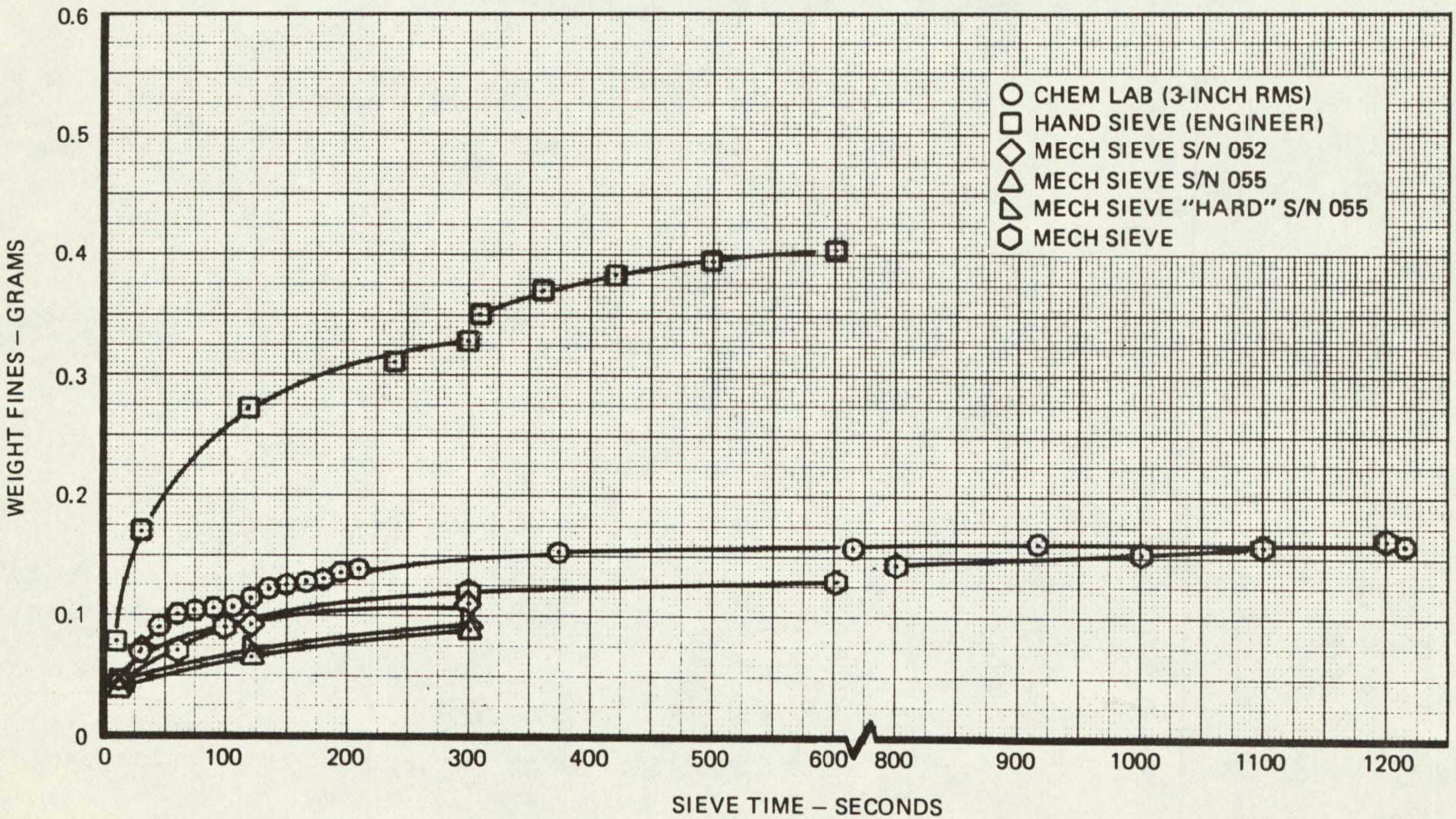


Figure 3-12

TABLE 3-11

CONTROLLED LOAD FIXTURE TESTS

Injector S/N	052D	055B	055C	054B	055D
Presieve Time Sec	300	300	20	40	300
Type Catalyst	Normal	Normal	"Hard"	"Hard"	"Hard"
Load, grms	1.81	1.89	1.96	1.94	1.95
Fines Incl. 30 Mesh Ret					
grms	0.03	0.07	0.06	0.23	0.04
%	1.7	3.7	3.1	11.9	2.1
Fines Excl. 30 Mesh Ret					
grms	0.01	0.06	0.02	0.22	0.03
%	0.1	3.2	1.0	11.3	1.5
Distribution of Fines (% in Size Range)					
30-40 Mesh	100	83	100	99	92
40-50 Mesh	-	9	-	1	4
50-60 Mesh	-	2	-	-	2
$<$ 60 Mesh	-	6	-	-	2
Post Pack Flush Results (No. of Particles in Size Range)					
$<$ 0.001"	88	49	228	47	166
0.001-0.002	4	3	17	4	10
0.002-0.004	0	4	0	0	4
0.004-0.005	0	1	0	0	0
$>$ 0.005	0	2	0	0	0

3.5.2 Welded Nozzle Tests

Concurrent with many of the foregoing unwelded packing tests, a series of tests were conducted to evaluate the effect of environment upon the packed injector assembly. Eight injectors were packed to the baseline packing procedure by two operators and subjected to the same environment as a flight T/VA. Table 3-12 summarizes the measurements made on each of these injectors. The two operators are differentiated by the amount of presieve time. One injector from each operator was welded and immediately disassembled as shown on the table. Referring to Table 3-10 shows an anticipated 0.05 grms of fines less than 30 mesh for 15-20 seconds of presieve time, applying this factor to S/N 035R on Table 3-12 indicates as much as 0.054 grms produced by the disassembly technique. Comparing this value to the fines found on the other welded injectors indicates that all fines from packing have been eliminated by firing the engine. Further, the water flush technique does not eliminate all these packing fines.

In a similar manner, Table 3-10 indicates 0.02 grms of fines less than 30 mesh for a 40 sec presieve. Applying this to Table 3-12, S/N 051R, results in 0.023 grms produced by disassembly. Therefore, only 2 mg of fines were found in the prefired injector and 9 mg in the prefired and vibrated injector as opposed to 20 mg in the water flushed and vibrated injector.

Throughout each of these operations, the injector inlets were taped. Figure 3-13 presents microphotographs of these pieces of tape after vibration. Injector S/N 035 is representative of the procedures used on F/N 024. The quantity and size of catalyst fines fro 15-20 sec per sieve time with previbration firing, is significantly less than water flush and approximately the same as 40 sec presieve. Figure 3-14 presents microphotographs of tape after disassembly. This figure again shows less fines on the prefired injectors, with a dramatic difference with or without vibration. In view of the amount of fines found in the packing study and disassembly it must be concluded that this high vibration level in the nozzle up attitude migrates the fines to the injector end. It must be noted however that some of these units plugged the capillary tube. Further, evaluation in light of the measurements of Table 3-2 leads to the conclusion that none of these photographs have more than 0.1 mg.

TABLE 3-12

PACKING STUDY

WELDED NOZZLE RESULTS

S/N	Presieve Time, Sec	Tests*	Catalyst Weights, g Loaded	Removed	Loss	Fines, <30 Mesh	Fines Wt, %
035	15-20	W, V	1.910	1.882	0.028	0.094	5.0
050	15-20	F, V	1.890	1.864	0.026	0.054	2.9
051	15-20	F	1.910	1.882	0.028	0.046	2.4
035R	15-20	-	1.900	1.818	0.082	0.104	5.7
036	40	W, V	1.852	1.820	0.032	0.043	2.4
053	40	F, V	1.860	1.840	0.020	0.032	1.7
052	40	F	1.871	1.830	0.041	0.025	1.4
051R	40	-	1.861	1.802	0.059	0.043	2.4

*W = Water Flushed V = Vibrated (LCSSE FA Levels) F = Previbration Fire

INJECTOR FLUSH RESULTS

Presieve Time, Sec	Tests	Number of Samples	Number of Particles in Size Range < 0.001"	0.001"-0.002"	0.002"-0.004"	0.004"-0.005"	>0.005"
15-20	W, V	1	19	14	2	0	0
15-20	F, V	1	102	80	9	0	1
15-20	F	1	51	8	2	0	0
15-20	-	1	163	15	0	0	0
40	W, V	1	56	8	0	0	1
40	F, V	1	29	1	0	0	0
40	F	1	136	17	1	0	0
40	-	1	278	22	0	0	2

TABLE 3-12

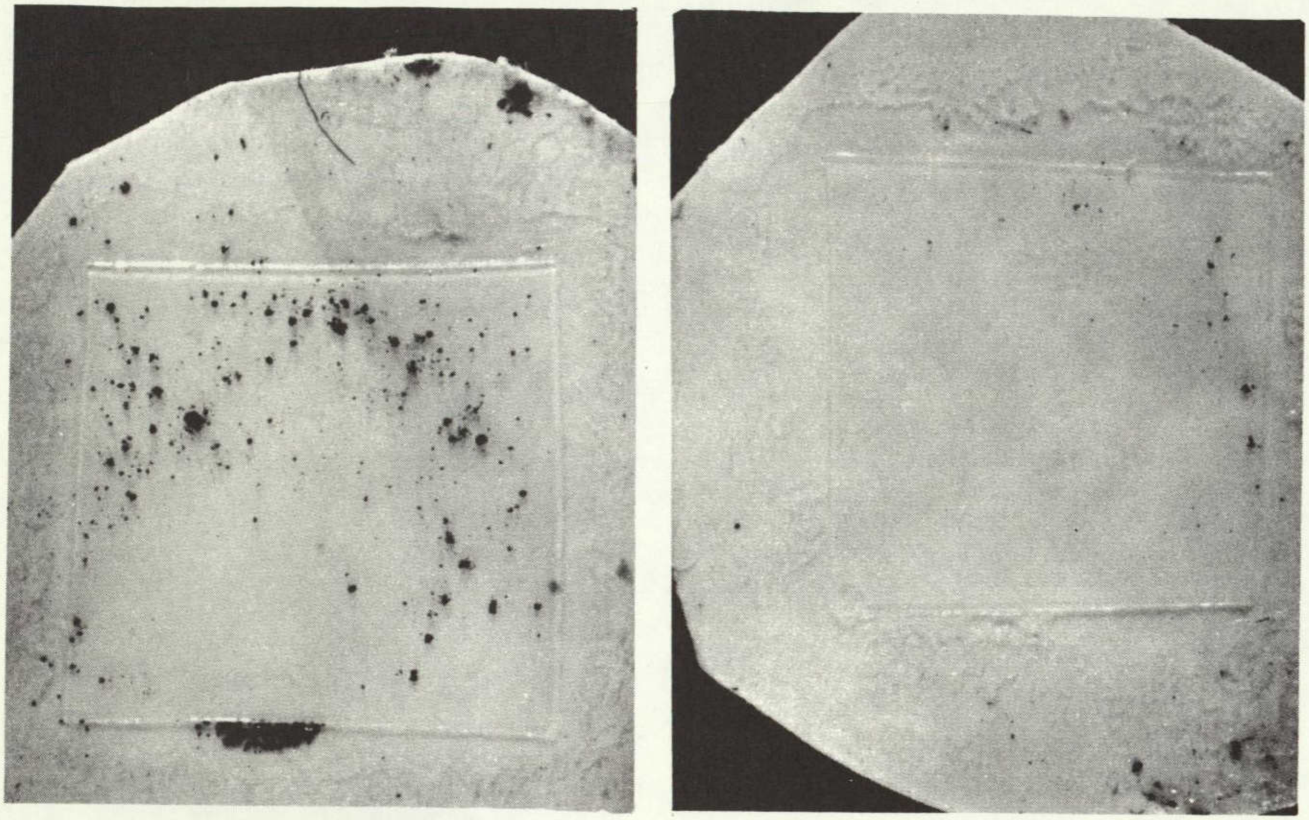
(CONTINUED)

WELDED NOZZLE TEST RESULTS (Continued)

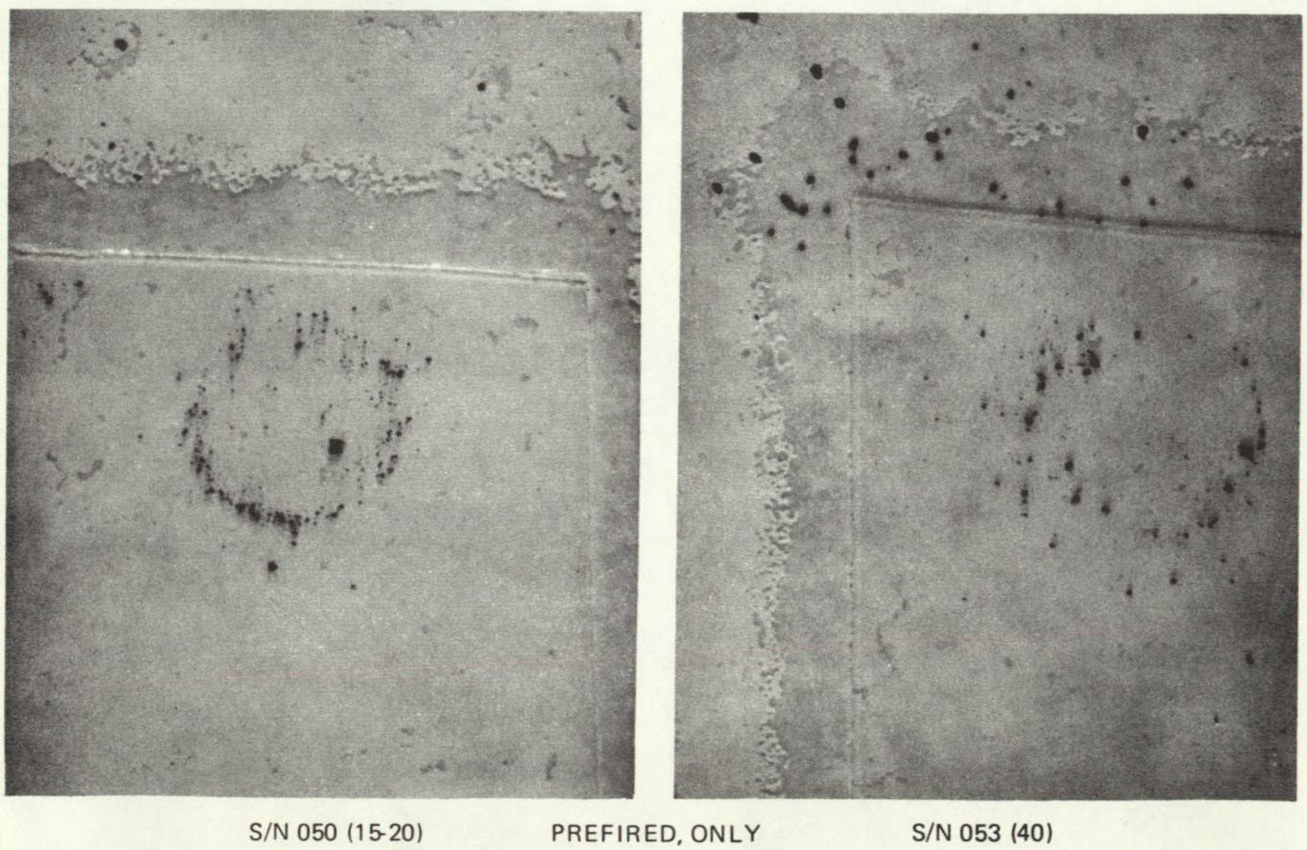
	15-20 Sec Presieve Time				40 Sec Presieve Time			
Fine Distribution	W, V	F, V	F	-	W, V	F, V	F	-
30-40 Mesh	71%	57%	63%	65%	81%	75%	56%	84%
40-50 Mesh	12%	17%	13%	17%	12%	9%	16%	9%
50-60 Mesh	5%	6%	9%	2%	2%	3%	4%	-
60 Mesh	12%	20%	15%	16%	5%	13%	24%	7%

PACKING STUDY WELDED ENGINE RESULTS

11 TIMES MAGNIFICATION OF TAPE OVER INJECTOR INLET AFTER VIBRATION
(LCSSE FA 3 AXIS–SINE)



S/N 035 (15-20) WATER FLUSHED, ONLY S/N 036 (40)

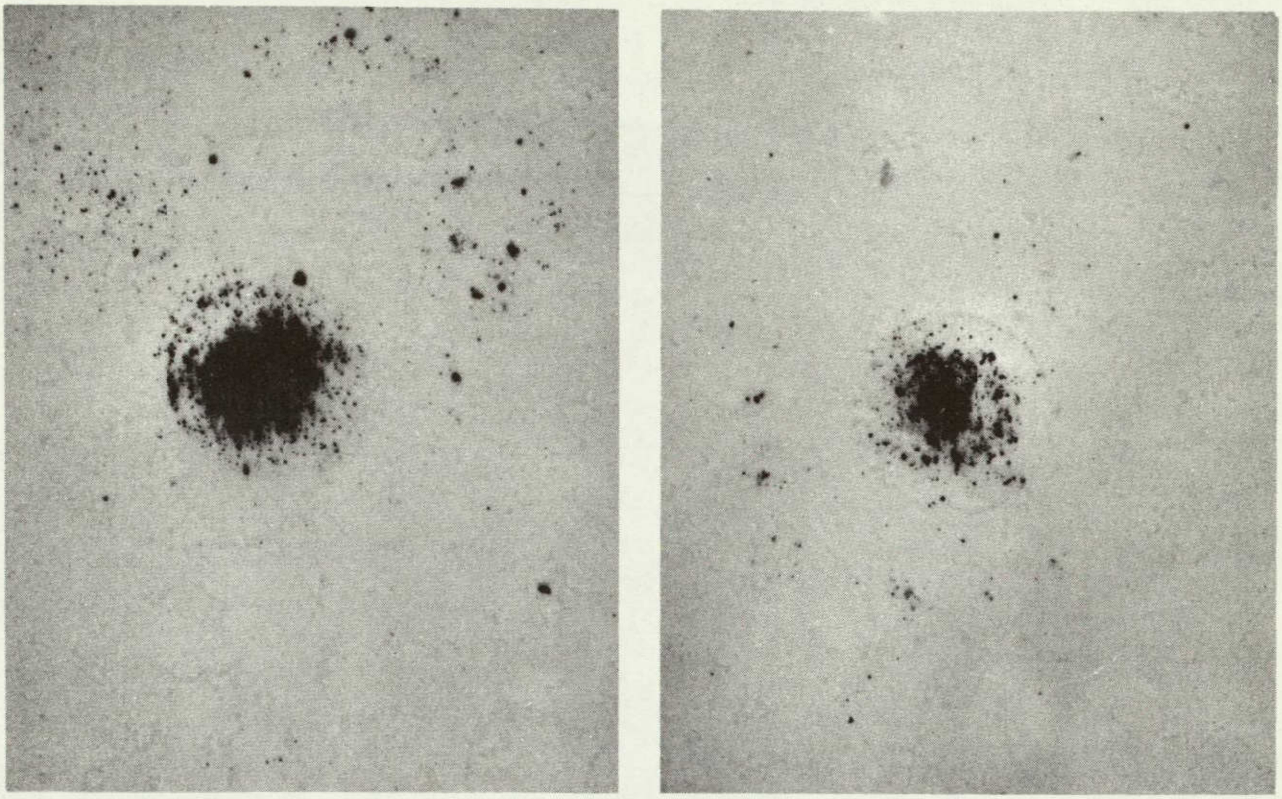


S/N 050 (15-20) PREFIRED, ONLY S/N 053 (40)

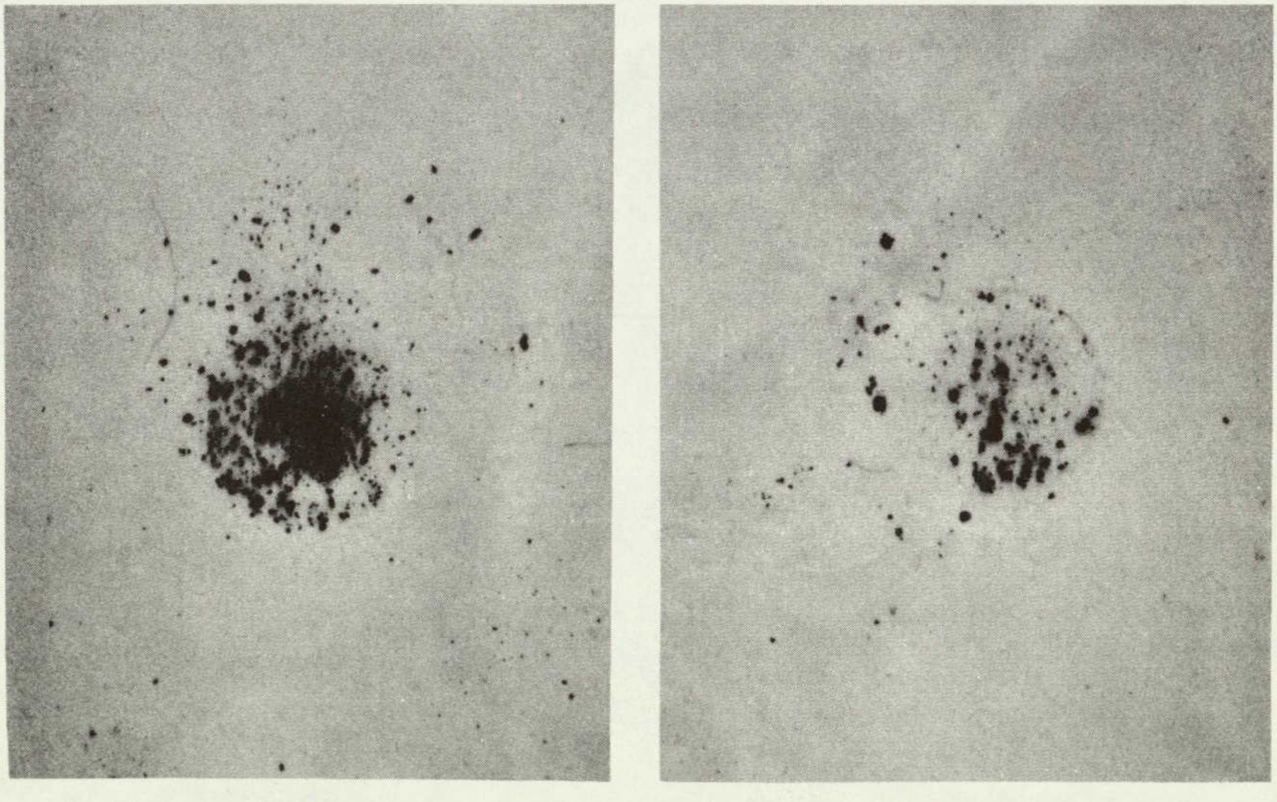
ORIGINAL PAGE IS
OF POOR QUALITY

PACKING STUDY WELDED ENGINE RESULTS

11 TIMES MAGNIFICATION OF TAPE OVER INJECTOR INLET AFTER DISASSEMBLY



S/N 035 (15-20) WATER FLUSHED AND VIBRATED S/N 036 (40)



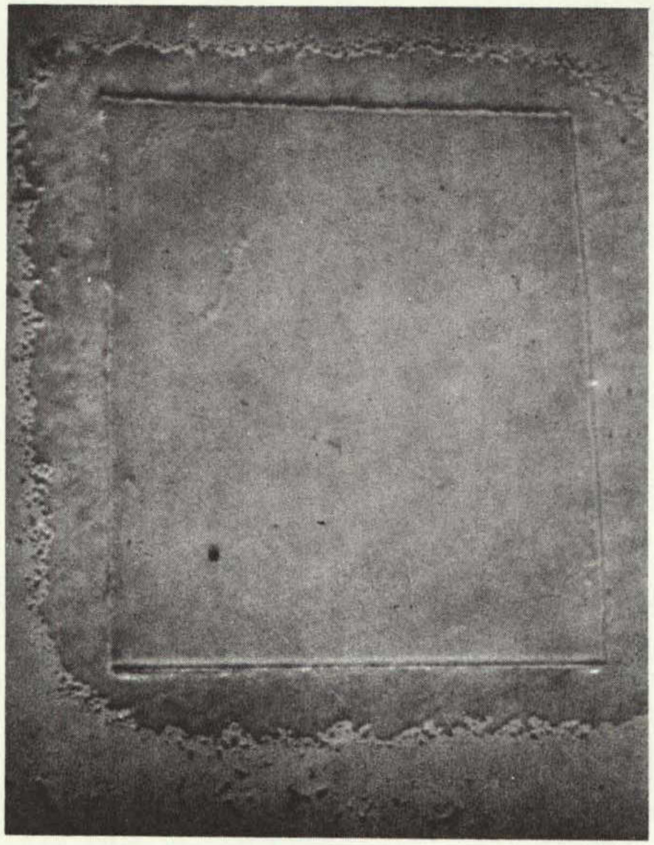
S/N 050 (15-20) PREFIRED AND VIBRATED S/N 053 (40)

ORIGINAL PAGE IS OF POOR QUALITY

Figure 3-13 (Concluded)

PACKING STUDY WELDED ENGINE RESULTS

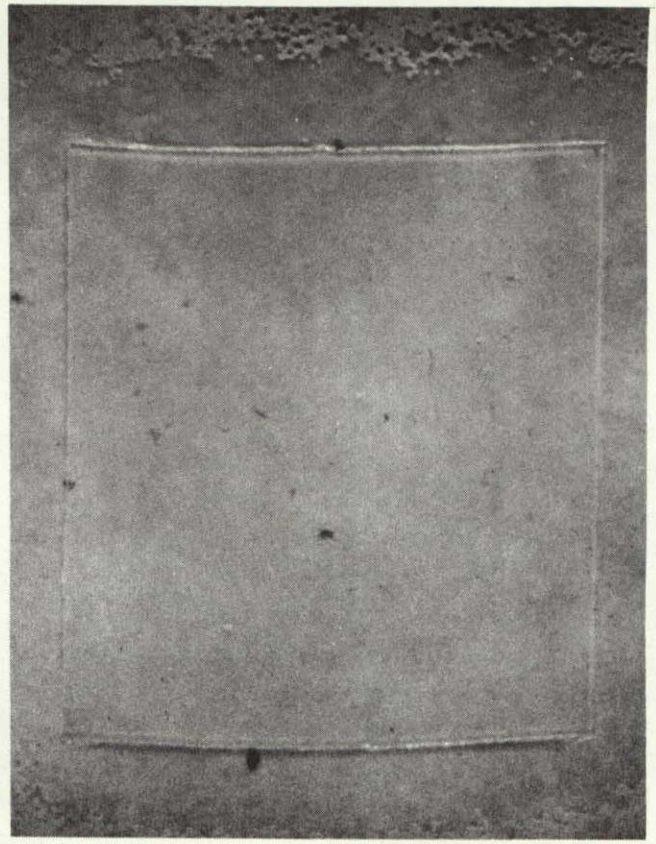
11 TIMES MAGNIFICATION OF TAPE OVER INJECTOR INLET AFTER DISASSEMBLY



S/N 051 (15-20)

SIMILAR
S/N 035R (15-20)

PREFIRED, ONLY



S/N 052 (40)

SIMILAR
S/N 051R (40)

Figure 3-14

4.0 CONCLUSIONS

The failure to fire of 0.2 lbf T/VA F/N 029 and 024 was the result of catalyst fines collecting in the capillary tube after their migration through the injector dispersion element. The particular capillary tubes involved were more susceptible to catalyst plugging than the baseline design configuration as a result of certain bend radii less than design allowables. The extremely high vibration levels, dictated by the generalized LCSSE requirements, amplified by the mounting structure of the particular design contributed significantly to the migration of fines. The evidence indicates a small amount of fines may be generated by the vibration itself. However, once an engine has been fired, expelling the majority of the fines, it is insensitive to handling or vibration attitude.

Design changes have been identified which should decrease the amount of packing fine migration prior to firing. These changes include 360 degree retention of the dispersion element and a fine mesh (new material) element. Although there is no predicted performance or environmental impact from such a change, it is mandatory that an environmental/life development test be conducted prior to implementation. Cost and schedule constraints of this program precluded such a test.

Modifications to the baseline program packing procedure have been identified which decrease the amount of fines packed into the catalyst bed. In particular both mechanical presieving of the catalyst bed for at least 300 sec and limits on the load exerted upon the catalyst bed (maximum equivalent to 200 psi) have been incorporated into the program. Additionally, water flushing of the packed injector assembly has been replaced with a previbration firing.

Although the MJS'77 environmental requirements represent a significantly lower vibration level, the present LCSSE levels will be maintained for this program. These levels will continue to provide an excellent acceptance screening test to provide maximum confidence in the hardware flight worthiness.

REFERENCES

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(2) "Interim Report" - External Catalyst Breakup Phenomenan, W. F. Taylor, Exxon Research & Engr. Co., and W. T. Webber, McDonnell Douglas Astronautics, AFRPL -TR-75-44, September 1975.

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