#### AD-773 195

## INTEGRATED RADIOSOTOPE CATALYTIC MONOPROPELLANT HYDRAZINE ENGINE

Ronald A. Carlson

TRW Systems Group

Prepared for:

Air Force Rocket Propulsion Laboratory

December 1973

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Three Radioisotope Heater Units (RHU's), delivering 1 watt of thermal energy each, were designed and fabricated using previously flight qualified designs. A minimal nuclear safety effort was thus required. The three RHU's were incorporated with the 5-pound thrust engine and tested to a duty cycle involving over 200,000 cycles with 565 "ambient temperature starts" (defined as 200°F minimum). The results of this test program are presented herein.

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# INTEGRATED RADIOISOTOPE CATALYTIC MONOPROPELLANT HYDRAZINE ENGINE

FINAL REPORT

TRW SYSTEMS GROUP ONE SPACE PARK REDONDO BEACH, CALIFORNIA 90278



RONALD A. CARLSON DECEMBER 1973

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AIR FORCE ROCKET PROPULSION LABORATORY DIRECTOR OF SCIENCE AND TECHNOLOGY AIR FORCE SYSTEMS COMMAND EDWARDS, CALIFORNIA 93523 AFRPL-TR-73-115

INTEGRATED RADIOISOTOPE CATALYTIC MONOPROPELLANT HYDRAZINE ENGINE

Contract F04611-72-C-0064

Final Report

December 1973

by

Ronald A. Carlson

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#### ABSTRACT

This report presents the results of AFRPL Contract No. F04611-72-C-0064 with TRW Systems Group. In this advanced technology program radioisotope heat sources were incorporated into an Integrated Radioisotope Catalytic Monopropellant Hydrazine Engine designed to maintain the catalyst bed above 200°F in an earth orbiting space environment. The impact of "ambient temperature starts" is thus reduced without requiring additional electrical power.

A limited development effort was conducted to upgrade a 5-pound thrust engine design originally developed during a TRW IR&D program. Iterations of the injector and headspace designs and variations to the catalyst bed were evaluated. Accelerated life testing of the selected design revealed a headscreen deformation problem and verified the design improvement incorporated to prevent recurrance.

Three Radioisotope Heater Units (RHU's), delivering 1 watt of thermal energy each, were designed and fabricated using previously flight qualified designs. A minimal nuclear safety effort was thus required. The three RHU's were incorporated with the 5-pound thrust engine and tested to a duty cycle involving over 200,000 cycles with 565 "ambient temperature starts" (defined as 200°F minimum). The results of this test program are presented herein.

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#### 1. INTRODUCTION AND SUMMARY

Anticipated requirements for monopropellant hydrazine reaction control thrusters to be used in future spacecraft missions include long operating life and numerous ambient starts. The rate of thruster performance degradation is influenced by the catalyst bed "ambient" temperature, leading to requirements for heating the catalyst bed. Electrical resistance heaters and radioisotope heaters are both capable of supplying the required heat energy. Resistance heaters require additional power from the spacecraft, however, and are comprised of components which are not conducive to high reliability for extensive spacecraft missions. Radioisotope heat sources do not have these limitations and are thus a promising approach to maintaining higher catalyst bed temperatures for extended times.

The objective of this program was to demonstrate the feasibility of an integrated radioisotope/catalytic 5-lbf class thruster with a capability of greater than 500,000 pulses independent of the number of ambient starts.

A limited development program was conducted to upgrade a 5-pound thrust engine design originally developed during a TRW IR&D program. The headspace injector design utilized in TRW thrusters has demonstrated excellent life capabilities, and the 5-lbf thruster was most directly applicable to the general requirements for this class. Pioneer 10 and 11 type Radioisotope Heater Units (RHU's) were then incorporated to supply 3 watts of nuclear heat energy. Three watts are sufficient to maintain a temperature of over 200°F for a thruster of this size in most earth orbiting spacecraft environments. The Pioneer 10 and 11 type RHU was selected for its flight-proven status, including nuclear safety approval for ground testing and launch. Minor modifications were required, however, to incorporate a pressure relief device in the isotope capsule. This was due both to higher temperature exposure (because of the close proximity to the catalyst bed), and to make it acceptable for earth orbiting applications.

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A demonstration test was conducted which accumulated over 200,000 cycles on the radioisotope heated engine, including over 550 engine ambient starts. Engine ambient for this program was specified as  $200^{\circ}$ F minumum and for test purposes was defined as  $210^{\circ}$ F ± 10.

The overall program as conducted is summarized in the flow of diagram presented in Figure 1-1.



Figure 1-1. Program Flow Diagram

Engine performance shifted gradually throughout the test because of an increasing catalyst bed pressure drop. The resultant thrust shift was 15 per cent at the high propellant inlet pressure and 27 per cent at the low pressure. There was no step change in performance, however, and the engine appears capable of continuing to deliver acceptable performance for much greater durations.

The engine was X-rayed and disassembled for post test hardware evaluation. Catalyst weight loss was also determined to be 1.7 grams or 8 per cent of the catalyst loaded; the catalyst bed was found to be in relatively good condition. Some fines were present, but there was no indication of voiding, severe compaction, or sintering. The catalyst separator screen fractured and separated from the chamber wall, and a small hole appeared in the headscreen. These failures had some impact on the engine response characteristics, but would not prevent the engine from operating for a more extensive duty cycle. An unheated engine, duplicating the pertinent design features of the heated engine, was fabricated and tested as part of the TRW IR&D program. The test exposure was the same as that for the heated engine except that each start was controlled to  $70 \pm 20^{\circ}$ F. Performance of this engine throughout the duty cycle was comparable to the heated engine. Post test hardware condition was also comparable except for a greater catalyst loss (13 percent).

Highlights of the thruster development program are presented in the succeeding sections along with a description of the final engine design. The engine test program is presented and the results discussed.

#### 2. THRUSTER DEVELOPMENT

TRW's headspace injection design has demonstrated long life capabilities at the 4  $lb_f$  thrust level. This thruster operates with high inlet pressure and was originally designed for a nominal 3  $lb_f$  thrust level, restricting its application within the 5  $lb_f$  class. IR&D testing of a 5  $lb_f$  thruster had demonstrated a good base point for a new thruster design which was more suitable to many current applications. A limited thruster development program was planned to select the final configuration.

This section summarizes the thruster development program. Starting with the baseline design, the test plans for the injector definition and for the lower catalyst bed definition tests are presented. Test results and resolution of specific problem areas are then discussed.

#### 2.1 BASELINE DESIGN

A baseline design for a "new" thruster in the 5  $lb_f$  thrust class is established from emperically derived criteria which include:

• Bed loading (G)  $\leq 0.03$  lb/sec-in<sup>2</sup> (based on engine cross-sectional

area)

- Hemispherical headspace design to a nominal throughput of 0.05 lb/sec-in<sup>2</sup> (based on total area)
- Layered catalyst bed

18-20 or 14-18 mesh upper bed 20-30 mesh lower bed

- Injection velocity 25-80 fps
- Injector spray pattern 60-110° included angle

The final parameter required to establish the baseline design is length of the catalyst bed. Pressure Drop considerations are of importance, but offer considerable leeway. Experience has shown that approximately 0.5 inch of 20-30 mesh catalyst is required for the lower bed to insure that flooding (washout) will not occur during extensive duty cycles. The upper bed length must be 0.1 to 0.2 inch longer than the axial length of the headepace. Using these dimensions, a bolt-up thrust chamber is designed for an iteration test program. The iteration test program establishes the final configuration of the injector, head space, and upper catalyst bed. Primary evaluation criteria are pulse repeatability (shape, impulse, and centroid) and chamber pressure roughness over the operating thrust range. Final adjustments to optimize the length of the lower catalyst bed are normally omitted due to the postulation that little benefit would be realized.

Figure 2-1 presents the bolt-up thruster design used for the test program, and Table 2-1 presents the baseline parameters. The bolt-on head end assembly provides rapid access to the catalyst bed and a removable injector element minimizes the cost of injector design iterations. The headscreen is held on the headplate by a pressed on retainer ring designed to an interference fit. Resistance welding or brazing are used at this attachment for extensive tests, while the interference fit has proven satisfactory for tests involving thousands of pulses. The catalyst separator screen is resistance welded to a ring which fits closely within the chamber and simulates a step in the chamber wall. For the bolt-up hardware, the location of this screen is set by the catalyst loading as the purpose of this this screen is usually to separate different mesh sizes of catalyst and is not a structural member.







#### Table 2-1. Baseline Design Parameters

Parameter	Nominal	Range	
Thrust (1bf)	5.0	2.1 - 5.6	
Propellant Pressure (psia)	300	100 - 350	
Chamber Pressure (psia)	180	70 - 200	
Bed Loading ( $G = 1bm/sec-in^2$ )	0.027	0.011 - 0.030	
Total Bed Length (in.)	1.0	1.0	

#### 2.2 INJECTOR DEFINITION TEST PLAN

The design criteria presented above offer considerable leeway in establishing a specific design. This test sequence evaluated the influence of design variations within the above criteria to select the "best" design.

Each candidate design was subjected to the duty cycle presented in Table 2-2. Repeat and/or special tests dicated by test results were tested to abbreviated sequences, however, to obtain only the most pertinent data.

Sequence	Duty Cycle	Propellan	t Feed Pressure(s) (psia)
1	500 Second Steady	State	350
2	Duty Cycle A	350, 225,	100, 500, and 50
3	Pulse Sweep*	350, 225,	100, 500, and 50
Sequence	Dr On-Time (msec)	Off-Time (msec)	Number of Pulses
 a	20	980	100
b	20	480	100
с	50	950	100
d	50	450	100
е	100	900	100
6	150	850	100
I	100	0.0	100

Table 2-2. Duty Cycle - Injector Definition Tests

\*A pulse sweep consists of a 10-second steady-state firing to heat the thruster, followed by a single test varying the pulse width (on time) from 0.020 to 0.150 second at a constant pulse rate of one per second. Chamber pressure, inlet pressure, and solenoid valve current were the primary data obtained. Chamber pressure and valve current were displayed on an oscilloscope and photographs taken which present several pulses superimposed. Data for selected portions of the tests were also recorded on an oscillograph as a backup for the oscilloscope photographs.

Evaluation criteria for the design selections are primarily chamber pressure oscillations, both during pulse mode and steady-state operation, and repeatability of pulse characteristics. Chamber pressure roughness is comparable on an absolute basis both in terms of nominal (average) magnitude and the magnitude of any pressure spikes or overshoots which may occur. Pulse repeatability is more subjective and is most easily evaluated using photographs of the oscilloscope trace. A semi-quantitative criteria for this evaluation is the number of distinct traces discernible from 10 superimposed pulses and/or the relative "line width" resulting.

Figure 2-2 presents the typical oscilloscope data obtained from a "pulse sweep." The 10 second steady state test is shown in the top photograph with an oscilloscope sweep rate of 1 sec/div. Immediately after the steady state test, pulsing is initiated at 0.150 sec ON - one pulse/sec and the oscilloscope set to sweep at 0.050 sec/div. The thruster is allowed to stabilize at this duty cycle and five (5) pulses are photographed. The pulse on time is then changed and the procedure repeated to show five (5) pulses each at pulse duration of 0.150, 0.100, 0.050, and 0.020 sec. on one photograph, After changing the oscilloscope sweep rate to 20 ms/div, the pulse duration is stepped up to again show five pulses each at the different pulse durations.

Fourteen (14) test sequences were planned to select the configuration of the injector and upper catalyst bed. Figure 2-3 summarizes the design iterations and test logic.

The first three tests were to determine the headscreen geometry and evaluate the low thrust operation of the baseline injector. TRW development experience has shown that thruster performance characteristics are more influenced by the addition of a small cylindrical extension of the headspace than by changes to the spherical radius, and that the headscreen design will not be significantly influenced by minor changes to the injector configuration.



Tests shown consist of a 10 second steady-state firing (first picture) followed by a single test varying the pulse width (on time) from 0.150 to 0.020 second on (second picture) and then from 0.020 to 0.150 second on (third picture) at a constant pulse rate of one per second. Five pulses at each pulse width are shown in each picture.

Figure 2-2. Typical Pulse Sweep



INJECTOR ITERATIONS





V = TBD



CATALYST COMPOSITION (UPPER BED)

- A 14 18 MESH SHELL 405 (75%) 14 - 18 MESH HA - 3 (25%)
- B 14 18 MESH SHELI. 405 (75°) 18 - 20 MESH HA-3 (25°)
- C 18 20 MESH SHELL 405 (75°) 18 - 20 MESH HA-3 (25°)

	H	EADSCREE	N	
	٨	B	С	1
INJECTOR A	٠	•	•	
	•	SELECTED HEADSCRE SELECT IN	EN JECTOR E	VELOCI
	CATALY	ST COMPC	SITION	
	•	B	С	1
INJECTOR A	٠	•	•	1
INJECTOR B	٠	•	•	
	•	SELECTED SELECTED VEL	BED INJECTI OCITY	ON
INJECTOR C	•			
INJECTOR D				
	•			
		SELECTED	INJECTO	R
	•	SELECTED VERIFY HE	N	R 1
		SELECTED VERIFY HEADSCREE	INJECTO ADSCREEM N C	]

Figure 2-3. Injector/Upper Bed Test Logic

The three headscreen configurations selected (see Figure 2-3) are derived from prior test history at the 5  $lb_f$  thrust level and scaling data from a series of tests which evaluated allowable tolerances for a 1.0  $lb_f$  nominal thrust engine. Another primary goal for these tests was to aid in the establishment of minimum injection velocity. Previously tested thrusters of this design concept have utilized injection velocities of 50 to 80 fps at nominal thrust, yielding 25 fps when operated at the low end of their thrust range. Operation of the baseline injector at reduced thrust determined the adequacy of the injection velocity and contributed to selection of an alternate design (lower velocity desired, higher if required).

The second series of tests lead to final selection of the injection velocity and the upper catalyst bed composition. Two injectors, identical except for size of the orifices (velocity), were evaluated with three catalyst bed compositions.

Upper catalyst bed design involves a tradeoff between bed porosity (increased by larger mesh catalyst) required to enhance recirculation of hot gases within the headspace, and effective catalyst activity (resulting from smaller mesh catalyst) required to initiate decomposition. If the catalyst is too fine (i.e., 20-30 mesh), recirculation is restricted and propellant tends to collect within the headspace and cause pressure spikes through random decomposition. Too coarse a mesh (i,e., 14-18 in smaller reactors) will result in poor initial response and spikes occurring during the pulses. Previous testing at the 5 lb<sub>f</sub> thrust level selected a bed composition consisting of 75 percent 14-18 mesh Shell 405 and 25 percent 18-20 mesh HA-3. This testing was very limited, however, and a more uniform mesh size is desirable to minimize catalyst migration.

Two additional injectors were then designed to evaluate alternate spray patterns, maintaining injection velocity constant. The baseline design was initially scaled up from smaller thrusters. The alternate designs selected (see Figure 2-3) represent a scaled down version of a larger thruster and an intermediate between the other two.

A final survey of the headspace design was planned to verify the selection of the headscreen for the specific injector selected.

#### 2.3 LOWER CATALYST BED DEFINITION TEST PLAN

A significant factor in the life related degradation of thruster characteristics is the compaction of the catalyst bed and accumulation of catalyst fines, resulting in increased pressure drop. These rendencies can be reduced by increasing the porosity of the catalyst bed, decreasing the bed pressure drop, and/or decreasing bed length. These factors all interrelate, and all impact the performance characteristics. Increased bed porosity (larger mesh catalyst) impact the response characteristics and, generally, necessitates an increase in bed length to insure that flooding will not occur. Testing at the 1.0 lbf thrust level indicated that a total bed length of 0.6 inch, comprised of 0.3 inch 18-20 mesh and 0.3 inch 20-30 mesh catalyst, was adequate. Real-time duty cycle tests (for the specific application) demonstrated an increasing tendency to flood (incomplete hydrazine decomposition), however, during long steady-state firings. At that time, cost and schedule dictated a conservative approach and the length of the lower catalyst bed was doubled. The fact that the initial design was marginal supports the theory that larger mesh catalyst could have been used to extend the lower bed with equal success in preventing flooding.

An approach used in the design of gas generators which utilize very long catalyst beds (to enhance ammonia dissociation) is to layer the bed. The screens used to define the layers support the catalyst, reducing the maximum compression load resulting from bed pressure drop. Additional porosity at each screen also enhances uniform flow distribution through the remainder of the bed.

Previous testing had demonstrated that 20-30 mesh catalyst was required for the lower bed in order to meet the response requirements imposed. A small compromise in response characteristics may, however, yield a better overall design for long life. Two additional tests (as used during the injector definition phase) were planned to evaluate the effects of using 18-20 and 14-18 mesh catalyst for the lower bed.

Four iterations of the lower bed design were planned to select a design least sensitive to clogging with catalyst fines and verify that the design would not be prone to flooding during steady-state firings. This was to be

accomplished by selecting two candidate designs and simultaneously subjecting them to the accelerated duty cycle presented in Table 2-3. The design demonstrating the least change in performance characteristics would then influence selection of two alternate configurations. Figure 2-4 presents the original logic and tentative design selections for the first test.

Sequence	Duty Cycle	Prop	ellant	Fee	d Pro	essu	re(s)
1	500 Second Steady State			350	-	-	-
2	Duty Cycle A (Table 2-2 )	350,	225,	100,	500	and	50
3	Duty Cycle A	350,	225,	100,	500	and	50
4	Pulse Sweep (Table 2-2)	350,	225,	100,	500	and	50
5	Duty Cycle B			350			
6	Repeat 3, 4 and 5 - three times						
7	Repeat 3 and 4						
8	2,000 Second Steady State			350			
9	Duty Cycle A	350,	225,	100,	500	and	50
10	1,000 Second Steady State		-	500			
NOTE :	Thrust data will be obtained for se	quences	1, 2	, and	9 0	only.	

Table 2-3. Duty Cycle - Accelerated Life Test

_		Du	aty Cycle B		
	Sequence	On-Time (m sec)	Off-Time (m sec)	Number of Pulses	
	a	20	230	1000	-
	ь	50	200	1000	
	c	100	150	1000	
	d	150	100	1000	
	e	100 sec	Steady State	1	
	f	Repeat a	thru e, 6 times	24,006	



#### Figure 2-4. Lower Catalyst Bed Iteration Tests

#### 2.4 INJECTOR DEFINITION TEST RESULTS

The headscreen iteration testing (see Figure 2-3) showed good steady state operation, particularly with Headscreens B and C. Pulse mode operation, however, showed pressure overshoots on startup followed by damped cyclic oscillations. Figure 2-5 presents a summary of the analog test data.

The pressure overshoot was attributed to insufficient liquid pressure drop, and the pressure distribution was re-evaluated. The IR&D thruster had been tested with a nominal chamber pressure of 100 psia (at 5  $lb_f$ thrust). That design was dictated by the availability of a valve which had a high pressure drop. A higher chamber pressure was selected for this program to reduce the catalyst bed pressure drop and to reduce the nozzle exit diameter. The latter factor was primarily to reduce the heat loss by radiation. At this point, however, it was decided to revert back to the IR&D design having the lower chamber pressure (Reference Table 2-6).

Changing to the lower chamber pressure at this point necessitated a change to the nozzle expansion area ratio ( $\epsilon$ ). Preliminary design of the



Figure 2-5. Injector Definition Test Results

final engine led to selection of a casting for the thrust chamber and ports for the radioisotope heater units (RHU's). Accounting for the lead time to receive castings, a casting was designed which provided adequate flexibility for any anticipated design iterations. Only minor changes to this design were necessary to increase the nozzle throat diameter (thus lower chamber pressure) provided the nozzle exit diameter remained essentially unchanged. The nozzle expansion area ratio was thus changed from 40 to 24.

Limited testing was continued with the baseline design, pending fabrication of new nozzles, Headscreen C (0.44 inch length) was selected as shown in Table 2-4. The design for Injector B was also selected from this test series. An increase to the injector velocity appeared desirable for operation at lower thrust levels. Slightly less than twice the injection velocity was chosen for the second injector (Injector B). An orifice diameter of .009 inch, yielding a nominal velocity of 44 fps, was selected.

Table	2-4.	Headscreen	Performance	Comparison
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Pinlet	He	Headscreen A			Headscreen B			Headscreen C			
(psia)	Steady State	ate Pulse Mode		Steady-State Pulse Mode	se Mode	Steady-State	Pulse Mode				
	Pc Roughness	Overshoot	Repro.*	Pc Roughness	Overshoot	Repro.*	Pc Roughness	Overshoot	Repro.*		
350	+10%	52%	2	+52	30%	2	+4%	22%	1		
225	+90%	2 3 %	1	<u>+</u> 7%	0	1	<u>+</u> 7%	0	1		
100	+22%	0	2	+31 %	0	1	+223	0	1		

\*Reproducibility Ratings:

1) Good Reproducibility

2) Minor Variations

3) Erratic pulse-to-pulse variations

Catalyst for the above tests was 100 percent Shell 405, 14-18 mesh for the upper and 20-30 mesh for the lower catalyst beds. Tests were then conducted to evaluate the alternate upper catalyst beds as well as the alternate injection velocities. These tests were first conducted with the high Pc chamber. Injector A (25 fps) performed best with catalyst C (18-20 mesh) and Injector B (44 fps) performed best with catalyst A (14-18 mesh). The results were verified using the low Pc (100 psia) chamber as shown in Figure 2-6. The lower injection velocity was selected for further testing, in conjunction with catalyst C (18-20 mesh). Table 2-5 presents the comparison of the three injector spray patterns and Figure 2-7 presents a summary of the analog data. For overall performance Injectors A and D (60° and 50-110° injector spray pattern angles respectively) were rated essentially equal. Injector D was thus tested with an alternate headscreen (B) to verify that the prior headscreen selection was also applicable to this injector. No improvement was noted with the alternate headscreen. Injector A was selected at this point primarily because of ' similarity to the other TRW thruster designs.

Table 2-6 summarizes the results of the Injector/Upper Catalyst Bed Testing, presenting the baseline design parameters and the selected design.

Pislet		Injector	A	Injector B			
(bere)	Steady-State	Steady-State Pul		Steady-State		se Hode	
	Pc Roughness	Overshoot	Reproducibility*	Pc Roughness	Overshoot	Reproducibility*	
350	<u>+38</u>	0	1	<u>+92</u>	0	1	
225	±41	0	1	+9X	0	2	
100	+71	0	1	<u>+</u> 7%	0	1	

Table	2-5.	Injecto	r Performance	Compart	son
-------	------	---------	---------------	---------	-----

inlet		Injector	C	Injector D			
(psia)	Standy-State	Pulse Hode		Steedy-State	Pulse Mode		
	Pe Roughness	Overshoot	Reproducibility*	Pc Roughness	Overshoot	Reproducibility*	
350	+38	0	1	<u>+4</u> 2	0	1	
225	+61	0	1	+42	122	1	
100	+15%	0	1	±7%	0	1	

\*Reproducibility Ratings:

1) Good Reproducibility

2) Minor Variations

3) Erratic pulse-to-pulse variations



Figure 2-6. Injection Velocity/Catalyst Composition Test Results



Figure 2-7. Alternate Injector Evaluation

 Parameter	Baseline	Design	Selected Design
Propellant Pressure	300		300
Thrust (1b <sub>f</sub> )	5		5
Chamber Pressure (psia)	180		100
Llquid Pressure Drop (psid)	105		173
Catalyst Bed Loading (G - 1b/in <sup>2</sup> sec)	0.03		0.03
Catalyst Bed Pressure Drop (psid)	15		27
Nozzle Expansion Area Ratio (ɛ)	40		24
Injector Spray Angle	TBD		600 (Injector A)
Headscreen Length (inch)	TBD		0.47
Upper Catalyst Bed	TBD		18 - 20 mesh (Catalyst C - 25% HA-3)

Table 2-6. Thruster Design Comparison

# 2.5 LOWER CATALYST BED TEST RESULTS

Two "new" injectors were fabricated to the same drawings as the "selected" Injector A, and two thrusters assembled. One of the thrusters utilized 20-30 mesh and the other 18-20 mesh catalyst for the lower bed, with all other parameters identical. The "acceptance" test of these thrusters did not demonstrate the same performance characteristics as previously measured, however. Both thrusters demonstrated higher chamber pressure oscillations than anticipated. Figure 2-8 shows the steady state characteristics of these thrusters.

The difference between the thrusters was traced to fabrication differences of the injector element. The first injector was out of tolerance on wall thickness, yielding a low L/D for the orifices. Comparing this injector to the "new" injector A's showed the first to produce greater atomization and distribution of the propellant. All of the injectors were then



Engine #1 18-20 mesh lower bed



Engine #2 20-30 mesh lower bed



Prior Test Original Injector A (Reference)

Figure 2-8. Accelerated Life Test First Attempt

re-evaluated in water flow and visual inspection, and the original A was the only one found discrepant.

Reviewing the selection of Injector A (Section 2.4), it and Injector D (50° and 110°) were rated essentially equal. A second injector of this configuration (Injector D) was then fabricated and tested to verify that it repeated the earlier test results. Program scope limitation dictated continuation of the planned testing with Injector D rather than pursuing a further investigation of injector design parameters and/or attempting to reproduce the first injector.

Each engine was successfully "acceptance" tested, including measurement of thrust and propellant flow. Both engines were then installed to fire simultaneously and measure chamber pressure only. The intent was to rapidly accumulate 130,000 pulses on both thrusters, per the duty cycle of Table 2-3, then mount each thruster separately for thrust measurement for comparison of the lower catalyst bed compaction (as indicated by thrust shift). The 1,000 second steady state test at the high (500 psia) inlet pressure was to test for washout. Testing of the thruster having the 20-30 mesh lower catalyst bed was terminated after 83,600 pulses, however, due to a failure of the chamber pressure tap. Attempts to reweld this tube were unsuccessful. The remainder of the test was thus completed using only one thruster design. Data from these tests are presented in Figures 2-9 through 2-16, and Figure 2-17 summarizes the analog characteristics via pulse sweeps at various stages. Engine No. 1 has 18-20 mesh and engine No. 2 has 20-30 mesh catalyst for the lower bed.

Two variances from the plan evolved from the results of this test. The digital data revealed lower impulse and specific impulse at duty cycles of two (2) pulses/sec that at one (1) pulse/sec, leading to a re-evaluation of the catalyst blend. Post test evaluation of the hardware then revealed severe deformation of the headscreens. These factors are discussed separately in the following sections.

#### 2.5.1 Catalyst Blend Evaluations

Catalyst blends consisting of 25% HA-3 and 75% Shell 405 have been utilized to improve steady state chamber pressure roughness in certain thrusters. The blend has also been used in the upper catalyst bed of a



Propellant Pressure (psia)

Figure 2-9. Engine No. 1 - Chamber Pressure vs Inlet Pressure



Propellant Pressure (psia)

#### Figure 2-10.

Engine No. 1 - Thrust vs Inlet Pressure


Propellant Pressure (psia)

Figure 2-11. Engine No. 1 - Pc Integral vs Inlet Pressure











Propellant Pressure (psia)



Engine No. 2 - Chamber Pressure vs Inlet Pressure



Propellant Pressure (psia)

Figure 2-15 Engine No. 2 - Thrust vs Inlet Pressure



Propellant Pressure (psia)

Figure 2-16 Engine No. 2 - Pc Integral vs Inlet Pressure



-Summary of Operating Characteristics - Accelerated Life Test No. Figure 2-17. 0.5 lb thruster for high pulse rate (10 cps) operation. Review of the digital data from the acceptance tests of the accelerated life test engines, noting lower impulse from two pulse/second than from one pulse/ second operation, led to a re-evaluation of the use of a catalyst blend.

A comparison of the performance of the blended catalyst and all Shell 405 is presented in Figure 2-18 and Table 2-7. Steady state roughness is clearly reduced by the addition of HA-3 ( $\pm$ 3% vs  $\pm$ 12%). The impact on pulse performance is less clear, however. As shown in Figure 2-18, the chamber pressure response improves at the higher pulse rate for the all Shell 405 catalyst bed whereas the opposite is true for the catalyst blend. Further investigation into the use of catalyst blends was deemed beyond the scope of this program, and the use of 100% shell 405 catalyst was considered most appropriate. A compromise in steady state roughness was thus accepted and HA-3 catalyst deleted from further testing.

Pinlet (psia)	7	Catalyst 5% Shell 405/2	C 52 HA-3		All Shell 44	05
	Steedy-State	Pul	ie Hode	Steady-State	Pul	ie Mode
	Pr. Roughness	Overshoot	Reproducibility*	Pc Roughness	uvershoot	Reproducibility
350	<u>+</u> 2X	138	2	<u>+6</u> X	132	1
225	<u>+</u> 2X	0	1	<u>+</u> 7%	62	1
100	+42	0	1	<u>+</u> 11%	0	1

Table 2-7. Catalyst Performance Comparison

\*Reproducibility Ratings:

1) Good Reproducibility

2) Minor Variations

3) Erratic pulse-to-pulse variations

## 2.5.2 Headscreen Deformation Evaluation

Disassembly of the two thrusters used for the first accelerated life test revealed gross deformation of both headscreens as shown in Figure 2-19. Potential causes of this deformation include differential expansion of the catalyst and chamber, and thermal stresses in the headscreen due to localized cooling.



Figure 2-18. Catalyst Composition, Shell 405 vs HA-3 Blend

Both headscreens grossly deformed.



THRUSTER #1 134,740 PULSES



THRUSTER #2 83.600 PULSES

Figure 2-19. Headscreen Condition, Post Life Test No.1

The startup transient, particularly from an ambient start, involves heating of the catalyst and the chamber wall. Heating of the catalyst occurs faster than the chamber wall, as represented in Figure 2-20. The resultant temperature differential causes thermal stresses in the form of a compressive load on the catalyst. The compression load is in part supported (or applied) by the headscreen, which is also likely to heat rapidly due to its small mass. The resultant compression load on the headscreen may cause a slight deformation. As thermal equilibrium is attained, the greater coefficient of thermal expansion of the Haynes 25 chamber compared to the catalyst relieves this compressive load and loosens the catalyst bed. Migration of catalyst is then possible, due to the forces of gravity and/or flow forces, to fill the void generated by the screen deformation. After shutdown, compressive forces again occur via the chamber wall cooling faster and having a greater expansion coefficient than the catalyst. This cycle repeats with every restart from below equilibrium temperature for the given duty cycle. Hot restarts may, in fact, be more severe than cold starts due to reduced strength of the headscreen.

The above discussion readily explains some headscreen deformation. It is difficult to accept that as the total explanation, however, for the gross deformation experienced. Thermal stresses within the screen wire resulting from localized cooling by incoming propellant could, however, add to the above forces and result in the gross deformation experienced.



#### Figure 2-20. Startup Temperature Transient

Tests were conducted to aid in the understanding of the problem and investigate alternate solutions. One proposed solution was a compartmentalized catalyst bed which would limit catalyst migration. A cylindrical screen was added to the headscreen, slightly smaller in diameter than the headscreen and extending to the catalyst separator screen. This would prevent catalyst migration from the periphery of the headscreen to the area of the deformation. This and a control engine (identical to one of the accelerated life test engine) were tested simultaneously to 20 thermal cycles from ambient temperature to over 1500°F (chamber wall temperature). This was accomplished by firing for 5 seconds steady state, then force cooling back to ambient temperature. Neither headscreen exhibited noticeable deformation.

Two more engines were then built up and subjected to 30,000 pulses. This test was very similar to the first accelerated life test, mostly at 4 pulses/second and stepping through the four pulse durations (0.020, 0.050, 0.100, and 0.150) every 1000 pulses. In addition, the engines were force cooled to below 150°F every 1000 pulses. After this test, the control engine showed moderate deformation of the headscreen. The headscreen with the added cylindrical screen also showed deformation but much less than the control engine. Relating the deformation in the control engine to the orientation to gravity during firing (the engines were fired horizontally) showed greater deformation of the other screen, however, was more indicative of thermal stresses. The conclusion drawn from these results

was that the catalyst expansion, related to heating faster than the chamber shell, contributes to headscreen deformation but is not the sole cause. Thermal stresses resulting from portions of the headscreen being cooled by the propellant on hot restarts may be the most important contributor.

Two approaches were then pursued to support the headscreen and/or reduce the thermal stresses. A headscreen retainer was designed and fabricated, as were alternate injectors. Figure 2-21 summarizes these configurations.

The headscreen retainer consists of six (6) equally spaced webs to support the screen. It appeared that the impact of this addition on thruster performance would be minimized by rotating the inner set of injector orifices, allowing maximum clearance for the webs between orifices (Injector E of Figure 2-21 as compared to the baseline of Injector D). Another injector (Injector F) was fabricated with an added orifice, in line with the thruster axis, to improve distribution of the propellant over the headscreen. Additional headscreens were fabricated using 30X30 mesh, 0.010 wire diameter screen as compared to 40X40 mesh, 0.009 wire diameter. This offers some increase in wire strength and an increase in porosity.

Fabricate headscreen retainer



Fabricate alternate injectors



Injector D





Fabricate 30 X 30 mesh, .010 wire diameter headscreens as compared to  $40 \times 40$  mesh, .009 wire diameter.

Injector E

Iteration tests to evaluate configuration changes and Accelerated Duty Cycle tests to evaluate screen deformation.

Figure 2-21. Headscreen Evaluation Tests

An accelerated life test as presented in Table 2-8 was conducted using Injector D with a 40 mesh headscreen and without the retainer (control engine) and Injector F with a 40 mesh headscreen and without the retainer. Following 80,000 pulses, both headscreens showed moderate deformation. Injector F caused greater deformation, however, and was eliminated from further testing.

A series of iteration tests was then conducted to evaluate performance effects of 30 versus 40 mesh headscreens and of the headscreen retainer. These tests are summarized in Table 2-9.

Sequenc <b>e</b>	Duty Cycle	Propellant Feed Pressure(s) (psia)
1	Pulse Sweep	350, 225, 100, 500, and 50
2	100 sec SS	350, 225, 100, 500, and 50
3	Duty Cycle C, 8	times 350
4	100 sec SS	350, 225, 100, 500, and 50
5	Pulse Sweep	350, 225, 100, 500, and 50
		Duty Cycle C
Sequence	On-Time (m sec)	Off-Time (m sec) Number of Pulses*
а	20	230 2400
b	50	200 2400
с	100	150 2400
d	150	100 2400

Table 2-8. Duty Cycle - Accelerated Life Test

\* Approximate Number, change On-Time every 10 minutes.

### Table 2-9. Iteration Tests

Injector D1,*	40 mesh headscreen with retainer
Injector E	40 mesh headscreen without retainer
Injector E	40 mesh headscreen with retainer
Injector D1	30 mesh headscreen without retainer
Injector D1	30 mesh headscreen with retainer
Injector E	30 mesh headscreen without retainer
Injector D2	30 mesh headscreen without retainer
Injector E	30 mesh headscreen with retainer
Injector D2	30 mesh headscreen with retainer
Injector D1	30 mesh headscreen without retainer

\*Injector designations D1 and D2 represent the first and second of two identical injectors fabricated for the accelerated life test. The complete designation is included only as a record of the exact hardware tested.

Injector D and a 30 mesh headscreen were selected for use with the headscreen retainer. The close proximity of the propellant streams to the headscreen support webs evidently helps to prevent propellant accumulation. Another accelerated life test was then conducted with this configuration and an identical engine except for the headscreen retainer (D1 30 mesh without and D2 30 mesh with). Both engines looked very good after 80,000 pulses. The screen supported by the retainer deformed slightly over the retainer, assuming somewhat a hexagonal shape following the support webs. The unsupported screen deformed less than 40 mesh screens but in the same fashion, indicating that changing to 30 mesh screen is an improvement but gross deformation would ultimately occur.

A final accelerated life test was then conducted in which Duty Cycle C (Table 2-8) was repeated 29 times accumulating 280,000 pulses. The configurations tested were the same as the previous test (Injector D, 30 mesh screen, and with and without the headscreen retainer) to obtain another data point for a longer exposure. Results of this test were similar to the previous test, with even less deformation of the supported screen. Figure 2-22 shows the port test condition of the (6) headscreen subjected to accelerated life testing, and Figure 2-33 summarizes the engine characteristics over the final life test.



Figure 2-22. Headscreen Evaluation Test Results

None of the accelerated tests reproduced the gross deformation experienced from the first life test. The gross deformation is evidently the synergistic effect of several factors which are not clearly understood. Changing to the 30 mesh screen and adding the headscreen retainer grossly in increase the strength of the assembly, however, and no visual signs of damage to the retainer appeared. A single retainer was used for two tests, accumulating 360,000 pulses, adding to the confidence that it would survive the life goal.

#### HEADSCREEN DEFORMATION TEST DATA



NEW

80,000 PULSES

# Figure 2-23. Headscreen Deformation Test Data

### 3. ENGINE DESIGN AND FABRICATION

An iterative process was involved in arriving at the RCHE<sup>A</sup> design. Several concepts were reviewed in arriving at a base point from which to establish the final design. Some of these concepts, together with appropriate comments, are shown in Figure 3-1.

Based on the specified requirement of a 200°F catalyst bed and assuming a typical spacecraft environment in earth orbital missions, a heat source of about three (3) watts was assumed. Later thermal analyses proved this to be a reasonable assumption. The baseline design and the evolution into test hardware are discussed in the following sections.

## 3.1 BASELINE DESIGN

Selection of the baseline design was largely influenced by program scope inclications of a "new" heat source design. The design presented in Figure 3-2 utilizes Radioisotope Heater Units (RHU's) of the type flown on the Pioneer 10 and 11 Spacecraft, requiring a minimum nuclear safety effort to test and later to launch such an engine.

A casting was considered to provide the housing for three RHU's in close proximity to the catalyst bed. The chamber assembly bolts to the mount with thermal standoffs. Ceramic washers are shown as the standoffs, but thin walled titanium soon replaced the more brittle ceramic as the baseline. A Parker propellant valve, developed and qualified for use on the P-95 program, also bolts to the mount.

Analyses of this design, as discussed in the following section, demonstrated the feasibility of attaining the 200°F goal using Pioneer type RHU's.

### 3.2 THERMAL ANALYSES

A preliminary thermal model of the engine was constructed to determine the severity of the temperature requirements and examine the effect of varying model parameters such as standoff and feed tube geometry, insulation thickness, and component emissivities (Figure 3-3). The model has 24 nodes and is coded to be run on a timeshared version of the TRW Thermal Analyzer Program (TAP). The relation of model nodes and resistances to the physical

\*Radioisotope Catalytic Heated Engine.

Г	CONFIGURATION	WEIGHT, LBM	ADVANTAGES	DISADVANTAGES
1		THRUSTER SHELL .61 INSULATION .20 BRACKET .36 HEATER .33 VALVE .40 MISC22.10	CONVENTIONAL THRUST CHAMBER DESIGN     EXISTING RHU DESIGN     REMOVABLE BRU'S WITH MAXIMUM FLEXIBILITY     LEAST EXPENSIVE TO DEVELOP	¢ MEAVIEST
2	Bits IT Jo         Bits IT Jo         Bits IT Jo           No.0         Image: IT Jo         Image: IT Jo         Image: IT Jo           No.0         Image: IT Jo         Image: IT Jo         Image: IT Jo           No.0         Image: IT Jo         Image: IT Jo         Image: IT Jo	THRUSTER SHELL .33 INSULATION .20 BRACKET .24 MEATER .51 VALVE .40 MISC20 1.88	WEIGHT IMPROVEMENT     REMOVABLE HEAT SOURCE     CONVENTIONAL THRUST     CHAMBER DESIGN	<ul> <li>SPECIALIZED RHU RE-ENTRY BODY</li> </ul>
3	SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FIGH SBL/FI	THRUSTER SHELL .33 INSULATION .20 BRACKET .24 HEATER .38 VALVE .40 MISC20 1.75	<ul> <li>WEIGHT IMPROVEMENT</li> <li>REMOVABLE HEAT SOURCE</li> <li>CONVENTIONAL THRUST CHAMBER DESIGN</li> </ul>	o SPECIALIZED RHU RE-ENTRY BODY
4		THRUSTER SHELL .46 INSULATION .09 BRACKET .20 HEATER .17 VALVE .40 MISC20 1.52	<ul> <li>MINIMUM WEIGHT</li> <li>EXISTING RHU DESIGN CONCEPT</li> <li>SWALLER DIAMETER</li> </ul>	IMPACTS THRUST CHAMBER DESIGN     MORE COMPLICATED MOUNTING     LONGER
5	HURDENT'S SARANY HURDENT'S SARANY HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDENTS HURDEN	THRUSTER SHELL .22 INSULATION .12 BRACKET .24 HEATER .85 VALVE .40 MISC20 2.13	BETTER POSITIONING OF HEAT SOURCE     CONVENTIONAL THRUST CHAMBER DESIGN	<ul> <li>SFECIALIZED CAPSULE AND RE-ENTRY BODY</li> <li>MOST DIFFICULT RHU DEVELOPMENT</li> </ul>

# Figure 3-1. Comparison of Design Approaches





3-4

4

engine is indicated in Figure 3-4. The assumptions of the model are:

- Thruster housing and feed tube are L-605. Propellant valve case is 300 series stainless steel. Mount bracket and threaded fasteners are 6A1-4V titanium alloy.
- Thruster is attached to bracket with three 6A1-4V titanium alloy cylindrical standoffs, each 0.250 OD by 0.005 wall by 0.707 long or equivalent.
- Propellant value is connected to thruster with 0.090 OD by 0.010 wall by 0.47 long L-605 tube or equivalent.
- Perfect thermal contact exists between all attached parts, except valve to bracket and bracket to vehicle resistances, which are arbitrarily set at one-tenth the net standoff resistance.
- The exterior surface of the uninsulated nozzle radiates to space with an emissivity of 0.18. The interior of the nozzle radiates to space with an emissivity of 0.43.
- In advance of detailed shape factor calculations, the upper three radial direction branches are assumed to radiate entirely to space at absolute zero, while the lower three radial branches radiate entirely to vehicle sink temperature.
- The multi-layer insulation covers a total radiant housing area of 25.3 square inches. The insulation is a 0.13-inch thick blanket of separated nickel 200 foils with an equivalent thermal conductivity of 0.17 Btu/hr-ft°F. The emissivity of nickel foil is 0.10.

Briefly, the six principal radial directions from the catalyst bed (node 1) are represented by six branches in the model ending in radiation to space (node 12) or to the vehicle (node 11). A seventh branch transmits heat loss from the nozzle (node 19) to space, while the final branch represents the forward conduction path from thruster to valve and bracket. The cooling effect of propellant flow on the valve is modeled by attaching it to a node maintained at an assumed propellant temperature of 40°F (node 24) through a resistance representing the convective hydrazine cooling inside the valve. In pulse mode simulation, this convective resistance ( $R_{20}$ ) has a low value during on-time and a very high value during off-time. A 0.13inch thick blanket of multi-layer nickel foil insulation with an equivalent thermal conductivity of 0.17 Btu/hr-ft-°F was assumed to cover the catalyst bed-RHU housing. This conductivity can be obtained by either interweaving the nickel foil layers with layers of quartz fabric or by dimping the foil



Figure 3-4. Location of Thermal Model Nodes

layers so as to maintain their separation. Either separation method is adequate from a thermal standpoint, and the final selection of insulation type would be made on the basis of fabrication cost, weight, and envelope.

Several runs of the preliminary thermal model were made using resistances consistent with current flight designs to determine temperatures of baseline configuration engine components in worst case cold soaks and worst case thruster firing modes. Figure 3-5 illustrates steady-state temperatures during space vacuum cold soak.

The model node representing the vehicle is maintained at 40°F during cold soak. As the catalyst bed temperature of 382°F exceeds the 200°F minimum temperature by over 100 degrees, some tradeoffs can be made to ease thermal standoff, feedtube length, or RHU power requirements while still maintaining a margin over the 200°F minimum catalyst bed temperature.

A preliminary search for the worst case thruster firing duty cycle was conducted by first running the model for the steady-state temperature distribution with the catalyst bed held at an assumed hydrazine decomposition temperature of 1800°F and a nozzle temperature of 1200°F. Figure 3-6 illustrates the resultant temperature distribution. The 40°F flowing propellant maintains the valve node at 48°F during steady state firing. Next, a transient soakback run was made using the temperature of Figure 3-6 as an initial condition, but with the propellant flow shut off. Heat soakback from the thruster to the propellant valve is shown in Figure 3-7. A peak valve temperature of 184°F was reached 3400 seconds after shutdown from steady-state operation (this is consistent with the analysis and test results for the Pioneer F/G TCA in which the peak valve temperature occurs 3600 to 3800 seconds after shutdown). Temperature distribution at this time slice are presented in Figure 3-8.

A 5 percent pulsing duty cycle (0.05 second ON/0.95 second OFF) initiated at the time of peak valve temperature was also evaluated and the results are shown in Figure 3-9. The valve temperature decreases in this case as the cooling from the propellant flow exceeds the increased heat input from the reactor.







Figure 3-7. Propellant Valve Temperature After Shutdown from Steady-State Thruster Firing

### 3.3 SELECTED DESIGN

The final design of the RCHE, less thermal insulation, is presented in Figure 3-10, and a photograph of the engine is shown in Figure 3-11. A machined casting is utilized to provide three RHU ports intimately attached to the catalyst bed. The catalyst retainer plate and screens are inserted through the head end and resistance-welded in place as part of the catalyst loading operation. The furnace-brazed injector assembly, including the injector, headscreen, and headscreen support, is then EB welded as the final closure.

Thin-walled titanium standoffs attach the chamber assembly to the mount, providing high thermal isolation. The valve bolts to the mount using spacers to provide clearance from the standoffs. An O-ring seal is provided at the valve/injector feed tube interface, allowing for the thermal expansion of the feed tube. Location of the end of the feed tube within





Propellant Valve Temperature with Typical Engine Pulsing at Peak Soakback Temperature







105440-73

Figure 3-11. RCHE

the valve outlet is established by measurements during engine assembly and cutting the valve spacers to the appropriate length. This minimizes the dribble volume while preventing an interference fit.

Adjustment of the liquid pressure drop (thus the thrust versus propellant inlet pressure) is accomplished with an orifice at the valve inlet. The orifice consists of a drilled hole in a blank VOI-SHAN soft seal. For test purposes, a filter was attached to the valve inlet with the orifice and this joint not broken unless mandatory.

Thermal insulation was delted from the design for test purposes. A multi-layer insulation was assumed for the analysis. In order for this or alternate types of insulation to be effective, a vacuum on the order of  $10^{-5}$  torr must be maintained. This being impractical for hot fire testing, it was decided to delete insulation entirely and supplement the RHU's with a radiant heater in order to maintain 210 + 10°F.

#### 3.4 FABRICATION

Based upon the baseline design, the longest lead time components were the propellant value and the thrust chamber casting. The value interface was thus established early in the program and the procurement inititated. Definition of the chamber casing was required, however, before the thruster design iterations were tested. The design was thus established to provide for any anticipated iteration. As discussed in Section 2.4, the iteration testing led to a change in the thruster nozzle diameter to reduce chamber pressure. This change occurred after the casting procurement had been initiated, but before the tooling had been completed. Only a minor tooling change was required to change the outside nozzle contour for the larger throat diameter, provided the nozzle exit diameter was not changed. This factor influenced the design which yielded a nozzle expansion area ratio  $(\epsilon)$  of 24.

Following completion of the iteration test program, machining of the casting and fabrication of the remaining piece parts were completed. The assembly sequence started with the injector. Orientation of the headscreen and headscreen retainer with the injector were established during water flow. The headscreen and the retainer are lightly held in place by the retainer ring, and this assembly rotated relative to the injector to

determine the orientation which yields the least indication of water collecting within the headspace. Once the optimum orientation is selected, the retainer ring is pressed into place. The flow characteristics are then verified as satisfactory (unchanged) and the assembly prepared for brazing.

A one shot braze was planned to attached the headscreen, headscreen support, propellant feed tube, and an insert (adapter for feed tube to headplate) to the headplate. The first braze attempt was not satisfactory, however. A slight movement of the headscreen and support resulted in a gap of approximately 0.015 inch between the headscreen support and the headplate. Prior to attempting any repair, the assembly was water flowed and the injector spray pattern through the headscreen assembly deemed acceptable. A second braze cycle, using a slightly lower melting point alloy, then successfully filled the gap.

The injector assembly was again water flowed to verify spray pattern and to set the pressure drop. An orifice was added at the valve inlet yielding a total pressure drop of 159 psia at a flow of 0.0225 lbm/sec. The orifice consists of a blank VOI-SHAN soft seal drilled and reamed to 0.029 inch diameter. After water flow, the valve and injector were flushed with alcohol and dried.

Loading of the catalyst was the next operation, and it was desired to determine the mass of catalyst loaded. All components of the thrust chamber together weighed 324.5 grams, and adding the weld fixture yielded 1192.7 grams. The catalyst to be loaded was also weighed at 26.5 grams with the "tin" used to contain it. After loading the catalyst, the weight of catalyst (with tin) remaining was 5.9 grams and the weight of the (unwelded) assembly with fixture was 1213.4 grams. These numbers yield 20.6 and 20.7 grams of catalyst loaded, implying an accuracy of approximately 0.1 gram.

The first attempt at the final EB closure weld of the injector assembly to the chamber yielded cracks in the weld. A review of the weld joint design revealed a design error allowing too great a gap at the joint, leading to the weld cracks. An EB weld repair was then attempted by first machining a groove, approximately 0.020 inch deep, and adding 0.020 diameter Hasteloy W weld rod. Cracks again appeared at the point where the

weld started and stopped. TIG welding, using Hasteloy W filler, was then successfully utilized to repair the weld. This welding was done in small increments, with an Argon purge through the catalyst bed and with wet asbestos packed around the chamber to minimize the impact on the catalyst bed. Subsequent dye penetrant inspection and proof pressure and leak tests proved the weld sound.

3.5 ENGINE WEIGHT AND COST COMPARISON

The actual weights of the RCHE and the unheated IR&D engine (XMRE-5) are presented in Table 3-1, showing 0.97  $lb_m$  difference. This weight difference could be reduced somewhat as weight was not a primary concern of this program.

	RCHE	XMRE-5
Thruster Shell	.72 lb <sub>m</sub>	.19 lb_
Catalyst	.05	.05
Caps for RHU Ports (3)	.14	-
Bracket	. 47	. 47
Valve	. 40	.40
Miscellaneous	.23	.23
RHU's (3)	.30	
	2.31 1b <sub>m</sub>	1.34 1b <sub>m</sub>

Table 3-1. Engine Weight Comparison

A cost comparison for the two designs is less straightforward, as unit costs are greatly influenced by quantities and specific program constraints. The chamber casting for the RCHE had a non-recurring cost of \$1600 and a unit price of \$65. Subsequent costs for machining, welding, and fabrication of other piece parts are comparable to an unheated engine. The Radioisotope Heater Units will have a non-recurring cost of approximately \$20,000 and a unit cost of \$6,500, assuming that the prior qualification status is acceptable for the specific application.

### 4. HEAT SOURCE

#### 4.1 DESCRIPTION

The heat source design selected was chosen because it is essentially an off-the-shelf heat source. Except for the PRD, it is identical to the Pioneer RHU which has been flight qualified and is being used in Pioneer 10 and 11. The PRD, however, is also a component which has been flight qualified for the Transit and Pioneer RTG heat sources. These Pioneer heat sources are aboard the same spacecraft as the RHU's. By using all flight qualified heat source materials, components, and fabrication and inspection techniques, the risk and development effort required were practically nonexistent. The specifications to which the Pioneer RHU's were qualified represent the most stringent set of spacecraft and aerospace nuclear safety requirements imposed on any radioisotope heat source to date. All required material, process, and inspection specifications are available. Hence, the selection of this design offered the greatest possibility of program success at minimum cost.

The RCHE and Pioneer RHU's are illustrated in Figure 4-1. Note that the only difference between the two heat sources is that the foam spacers at the ends of the radioisotope fuel have been removed and replaced by a PRD at one end. In the PRHU, a void volume was provided inside the liner so that helium from the radioisotope decay process could be accumulated without increasing internal pressure to unacceptable levels. To prevent the fuel from rattling in this void, foam spacers were used. The foam spacers were less than 10 percent of maximum theoretical density and hence over 90 percent of the void was available for helium storage. By using a PRD to relieve helium pressure, the void, and hence the spacers, were not required.

The RCHE heat source is a cylinder 0.875 inch in diameter and 1.860 inches long. Three RHU's are used in an RCHE; each RHU weighs 0.11 pound. The components are described in Table 4-1.

\* Pressure Relief Device





Component
Source
Heat
4-1.
Table

S

	Deisoisel Function	Material	Outside Diameter (in)	Thickness (in)	Outside Length (in)	Weight (1b)
componient	111111101 10111111					
Radioisotope	One watt source	PuO <sub>2</sub> solid	0.191		0.675	0.0072
Pressure relief device	Release helium, retain fuel		0.210	8	0.270	0.0055
Liner	Provide fuel compati- bility and containment	Ta-10W	0.250	0.020	0.986	0.0097
Strength member	Provide impact resistance	T-111	0.346	0,040	1.085	0.0287
Clad	Provide oxidation protection for strength member	Pt-20Rh	0.380	0.010	1.127	0.0103
Insulator	Thermal protection of capsule during reentry	Pyrolytic graphite	0.516	0.063	1.400	1110.0
Reentry	Reentry protection and aerodynamic profile to limit impact velocity	Poco AXF-50	۵.875 و.	0.177	1.860	0.0415
			Total We	ight		0.1140

## 4.2 HEAT SOURCE FABRICATION AND ASSEMBLY

The materials of construction and the configurations of the heat source have, as mentioned above, been successfully fabricated and utilized in the Pioneer RHU program. Raw material and process specifications, including material heat treatment and cleaning procedures, for the materials were available from the Fioneer RHU and Transit RTG programs. Figure 4-2 is a typical manufacturing plan showing inspection, acceptance, and qualification test steps planned to assure conformance with an equipment specification. Methods for producing the piece parts and the assembly procedures for the heat source are discussed below.

## 4.2.1 Piece Part Fabrication

All RHU components, including the fuel, were fabricated or purchased by TRW. Tube stock to the finished OD and ID was purchased and then machined to the proper length for the pressure relief device (PRD), liner, strength member and clad. Ta-10W rod is used to produce the filter component and seal plugs for the PRD. The filter component consists of a solid core having a thin layer of  $Al_2O_3$  applied by plasma arc spraying. The liner and clad end discs are stamped from sheet stock of the finished thickness and then coined to the final diameter. The strength member end discs are fabricated from sheet stock and ground to the required thickness. These parts are all inspected at TRW, then shipped to the fueling agency for fueling and welding. Meanwhile, at TRW, the pyrolytic graphite insulator bodies were finished machined on the OD and ID from tube stock and the end plugs were made from sheet stock. All heat shield reentry components were machined from blocks of Poco AXF-5Q graphite.

# 4.2.2 Capsule Fueling and Heat Source Assembly

The fueling of the RCHE was unique in that it was accomplished at a commercial facility. TRW issued a commercial contract to Donald W. Douglas Labs of Richland, Washington, to purchase the fuel in powder form, press and sinter it then assemble it into the structural components by welding. Typically, this operation would have been conducted at a government facility which typically requires AEC involvement and interagency agreements. A recent AEC policy statement, however, encourages the use of commercial fueling facilities by properly liscensed contractors. The fuel


capsules are then returned to TRW where they are assembled into the graphite components.

Fueling of the radioisotope capsule is an eight-step process as follows:

- 1) The PRD is welded into one end of the liner tube
- 2) One end closure disc is welded to the clad tube
- 3) The fuel is inserted into the liner body subassembly
- 4) The end closure disc is welded to the open end of the liner body
- 5) The liner subassembly is decontaminated
- 6) The PRD seal plug is punctured
- 7) The fuel/liner subassembly is inserted into the strength member and the end closure disc is welded to the end of the strength member body, decontaminated, and its seal is punctured.
- 8) The fuel/liner/strength member subassembly is inserted into the clad and the end closure disc is welded to the end of the clad body to produce the capsule, and decontaminated.

Assembly of the capsule into the graphite heat shield is a two-step process as follows:

- 1) The clad is punctured and the capsule is slid into the pyrolytic graphite tube body and the pyrolytic graphite end cap discs are fitted into each end of the tube
- 2) The capsule/pyrolytic graphite subassembly is slid into the Poco graphite heat shield body and the Poco graphite end plugs are screwed in place to produce the RHU.

For live-fueled units, visual examination only was utilized to assure surface integrity. The internal quality of all weldments was assured by microstructural analyses of simulated assemblies welded prior to and after completing the fabrication of the lot of capsules, as well as X-ray radiography. A lot is defined as all subassemblies welded at the same time by the same operator. Criteria for acceptance was based on the experience gained during the Pioneer RHU and Transit RTG programs.

# 4.3 OPERATIONAL CHARACTERISTICS

The radioactive decay process of Pu-238 produces alpha particles (helium), gamma rays, and neutrons, and as a result, heat. The rates at

which these products are created establish thermal power output versus time, helium release rates, and nuclear radiation fields. During the development of the Pioneer heaters, analyses and tests were conducted to determine the resultant operational characteristics of the heat source. Additionally, analyses and tests were conducted to determine the effects of the launch vibration, shock, and spin environments on the heater components. All of these data are directly applicable to the RCHE.

#### 4.3.1 Thermal Power Output

The equation for thermal power output versus time for the radioactive decay of P-238 is

$$P = P e o$$

where  $P_{0}$  = initial power  $\lambda$  = decay constant = 7.93 x 10<sup>-3</sup> (years<sup>-1</sup>)  $\theta$  = time (years)

Using this equation and an initial thermal output of 1 watt, the plot in Figure 4-3 was generated. Note that the power decays at a rate of approximately 3/4 of 1 percent a year and is nearly linear for the relatively short period of 10 years (short in comparison to the Pu-238 half life of 87.5 years). One watt of Pu-238 will thus decay to 0.93 watt in 10 years. If the mission duration is 10 years, this power is referred to as the endof-life power. It is this end-of-life power output that must establish the minimum thruster operating temperature of 200°F (using three heat sources).

#### 4.3.2 Radiation Characteristics

Calculations were made to determine the gamma ray and neutron dose rates expected in the vicinity of each RHU. The samma ray dose rates were computed with the QAD point kernel code using thirteen gamma ray groups, energy-dependent build-up factors, flux-to-dose conversion factors, and attenuation coefficients. The analyses were based on the characteristics of the cermet fuel form. The source spectrum used in the calculations was that for 2-year old plutonium dioxide having 1.2 parts per million Pu-236 and 80 percent Pu-238. The neutron calculations assumed a source of 3.0 x  $10^4$  neutrons/sec-gram of plutonium and attenuation inversely proportional





to the square of the distance. The self-attenuation for neutrons in the RHU was estimated to be only 5 percent. The flux-to-dose conversion factor was taken to be 0.13 mrem/hr per  $N/cm^2$ -sec. The neutron production rate was assumed to be independent of time.

The results of the radiation calculations are shown in Figure 4-4 for 1 watt of radioisotope. The dose from 3 watts is three times as large if the 3 watts are in close proximity. The neutron dose rate is seen to be approximately a factor of ten higher at all locations than the gamma ray dose rate.

## 4.3.3 Helium Management

The operating characteristics of the PRD have been analytically and experimentally rerified in the Transit development effort.\* The characteristics may be summarized as follows:

- The helium permeation rates of all PRD assemblies tested remained stable not only through short-term testing, but also during long-term, high temperature operation. (Test temperatures ranged from 70° to 2700°F and pressure differentials varied from 0.0015 to 300 psi.) Figure 4-5 shows the stable helium permeation history of a Transit PRD undergoing long-term testing.
- There is good correlation between predicted and experimental flow rates at various pressure differentials from room temperature to 2700°F, as shown for the Transit PRD's in Figures 4-6 and 4-7.
- At high pressure differentials, relative to normal operating conditions, the permeation mechanism of these vents changes from slip flow to viscous laminar flow, as shown in Figure 4-7. During this change, the effect of the pressure gradient on the permeation rate changes from a first order dependency (proportional to  $(\Delta p)^2$ ). Thus, the PRD's have, in effect, a built-in safety valve. If the helium pressure in the capsule should suddenly rise to a very high value in an accident mode due to sudden (nonsteady state) release of excess helium from the fuel, the flow increases rapidly to relieve the pressure.
- \* 1. Transit RTG Updated Safety Analysis Report, Volume III. Nuclear Safety Analysis Document, September 15, 1970 TRW (A)-11464-291











Figure 4-7. Correlation Between Predicted and Experimental Flow Rate of Transit PRD's at 2700°F

• Experimental testing has demonstrated the ability of the PRD to retain submicron thoria fuel simulant while maintaining a stable helium flow at all flow rates measured. The conclusions obtained from the fineretention test were verified by a test series conducted independently by Monsanto Research Corporation, Mound Laboratory, utilizing plutonium-238 dioxide (PuO<sub>2</sub>) powder consisting of particles of less than 1 micron.\*

#### 4.3.4 Launch Vibration and Shock

The one watt heat sources have been vibration tested and qualified for the Pioneer mission. These units were contained in a thruster assembly similar to the RCHE design. The vibration input requirements are shown in Table 4-2. In early tests the heat sources survived an input approximately 100 percent higher than these requirements (56g peak).

The pyrotechnic shock environment to which the heat sources have been qualified is shown in Figure 4-8.

 Transit RTG Updated Safety Analysis Report, Volume III. Nuclear Safety Analysis Document, September 15, 1970 TRW (A)-11464-291

## Table 4-2. Qualification Level Vibration Spectrum

Random

9 Minutes each Axis

Frequency (cps)	PSD Level g <sup>2</sup> /cps
20 - 100	Increasing from 0.0023 to 0.056 at a rate of 6 db/octave
100 - 1000	0.056
1000 - 2000	Roll off from 0.056 at 1000 cps

## Sinusoidal

Hz	<u>g's (zero to peak)</u>
5 - 38	*
38 - 55	29.2
55 - 90	15.0
90 - 200	3.0

0.4 inch double amplitude

Sweep rate one octave per minute

### 4.4 NUCLEAR SAFETY

As discussed in Section 4.0, the baseline RCHE heat source design is essentially identical to the Radioisotope Heater Unit (RHU) which was developed for the Pioneer 10 and 11 spacecraft. The only difference is that the RCHE RHU incorporates a vent to relieve the helium that is generated, which eliminates the need for tantalum foam spacers. Therefore, the extensive safety analyses and tests which were conducted for the Pioneer RHU\* are directly applicable to the RCHE RHU. This section summarizes the safety analyses and tests which were conducted for the Pioneer RHU.

<sup>\*&</sup>quot;Safety Analysis Summary Report for the Pioneer Radioisotope Heater Unit," PFG-273-324, TRW Systems, February 19, 1971.

# SHOCK RESPONSE SPECTRUM SPACECRAFT X, Y & Z AXES OUTRIGGER ASSEMBLY



Figure 4-8. Pyrotechnic Shock

For the RHU, extensive analyses and tests were conducted to verify fuel containment during and after launch pad aborts and ascent aborts. The launch vehicle for the RHU-equipped Pioneer Jupiter spacecraft is the Atlas/Centaur/TE 364-4 configuration. Abort of this launch vehicle on or near the launch pad could expose the RHU's to a combination of overpressure, shrapnel, prompt liquid propellant fireball, impact onto the pad, and the residual fire associated with burning of liquid or solid propellants. Analysis was utilized to determine the extent of these environments and to predict their effects on the RHU, and tests were utilized to verify the predicted effects. Launch pad abort tests to which the RHU's were exposed consisted of: (1) 915 psia shock overpressure, simulating a 12.8 percent TNT yield ground burst of the TE 364-4 motor, (2) simulated shrapnel from the TE 364-4 motor casing at a velocity of 1900 ft/sec, (3) a simulated liquid propellant, prompt fireball with a heat flux history similar to that resulting from conflagration of all the liquid propellants, (4) impact of the RHU's onto a smooth, unyielding medium at 160 ft/sec, and (5) a solid propellant fire of maximum possible duration (based on the maximum web thickness from a burning chunk of the TE 364-4 solid propellant). These test conditions represented the most severe launch pad abort environments expected. In no case was radioisotope fuel released from the fuel capsules during or after exposure to these test environments. It was predicted, however, that fuel could be released during a solid propellant fire, depending on the fire temperature, if the capsule contained only one or two months of accumulated helium. Fuel release could be caused by capsule rupture because of internal pressure.

Ascent aborts of the Pioneer launch vehicle may result in spacecraft reentry and breakup, RHU terminal reentry, impact of the RHU's onto land, and long-term exposure of the RHU's to air and soil after impact. These environments and their effects on the RHU's were extensively analyzed, and the results were verified through tests. The initial reentry conditions at 400,000 feet altitude which could be achieved through attitude misorientations

of the launch vehicle's final stage were calculated using a digital computer program which presented the spectrum of potential initial reentry velocities and flight path angles. An analysis was conducted to determine the altitudes at which the RHU's would be released from the spacecraft for a range of initial reentry conditions. The aerothermodynamic environments experienced by the RHU's were then computed and their effects, in terms of reentry member ablation, reentry member thermal stress, and capsule structural integrity, were predicted. Several tests were conducted in which the most severe predicted aerodynamic heating rates were imposed on the RHU's. These reentry tests indicated that, for the Pioneer Jupiter mission, fuel could be released from the RHU's during reentry in only two cases, (1) if the attitude misorientation of the final stage were such as to cause the RHU's to undergo a grazing reentry 25 months after fuel encapsulation, and (2) if the launch vehicle failure resulted in random orbital decay and reentry of the RHU's in excess of 20 years after fuel encapsulation. Both of these types of failures were due to the sealed configuration of the fuel capsule. That is, for the elapsed times discussed above, which resulted in an accumulation of helium, and for the corresponding reentry temperatures, the internal pressures at these reentry temperatures would cause rupture of the fuel capsules.

Drop tests from high altitude were conducted in order to measure the terminal velocity of the RHU's. Impact tests were then conducted in which the RHU's were impacted against smooth granite, at various angles of attack, at a velocity of 125% of the predicted sea-level impact velocity. In no test was fuel released, and in no case was even one of the capsule components breached. In the post-impact environment, in which the RHU could be exposed to air and soil, the near-ambient temperature of the RHU, as predicted and later measured, indicated that complete fuel containment would be provided.

Further verification of the reentry, impact, and post-impact capabilities of the RHU was provided in a test in which two RHU's were released from a U.S. Air Force booster during reentry. Although the conditions at which the RHU's were released from the booster did not simulate a severe reentry such as might be obtained by ascent aborts of the Pioneer launch vehicle, the RHU's were recovered and were found to be completely intact. The reentry members underwent an immeasurably small amount of ablation, and were not cracked by impact.

Figure 4-9 presents a summary of the post-test conditions of the RHU. The RHU capsule was only slightly deformed as the result of the overpressure test, as shown in Figure 4-9a and the clad was intact. The capsule which was exposed to simulated shrapnel is shown at the top of Figure 4-9b, and the simulated piece of shrapnel is shown in the lower portion of the photograph. Extensive clad removal is evident, but fuel was completely contained. Figure 4-9c shows the results of the liquid fireball test, in which partial clad melting occurred. In Figure 4-9d, for the solid propellant fire, interaction between the clad and strength member is evident, but fuel was not released. Figure 4-9e shows the RHU reentry members which were exposed to simulated random orbital decay, grazing, and steep angle reentries. In all tests, the reentry member remained integral. Finally, Figure 4-9f shows the impacted capsules, where it can be seen that only slight deformation occurred because of impact.

Addition of the pressure relief device (PRD) to the RHU eliminates the two potential failure modes defined for the Pioneer RHU. Both failure modes required a pressure buildup within the capsule prior to specific reentry conditions. The vent eliminates the pressure buildup and thus the failure modes.

In response to an AFRPL request, AFWL/SECQ conducted a preliminary Nuclear Safety Analysis of the RCHE. They conclude that the RHU's used in this engine design are improved versions of those already flown on the Pioneer 10 and 11 missions and that no further effort is required until an actual flight application is identified. It is expected that the Nuclear Safety Analyses conducted by AFWL and TRW will facilitate a quick approval.



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#### 5. RCHE TESTING

Testing of the RCHE followed the sequence typical of a qualification test program. The engine was acceptance tested, including hot fire tests, then subjected to a qualification level vibration environment prior to the duty cycle demonstration test. These tests are discussed in the following sections.

#### 5.1 ACCEPTANCE TESTS

Following a visual inspection of the assembly, a proof pressure test was conducted. A nozzle throat plug was installed, and connections made to the valve inlet (filter) and chamber pressure tap. The valve was then opened and the assembly pressurized to 600 psig with GN<sub>2</sub> for 5 minutes. The pressure was then reduced to 200 psig and all potential leak paths checked with a snoop solution. No leaks were detected. With the valve closed, the inlet pressure was raised to 300 psig, the thrust chamber vented through the chamber pressure tap, and internal leakage of the propellant valve checked. This was a bubble type test measuring through the chamber pressure tap. No leakage was detected over a 10 minute period.

The engine was then installed on the thrust stand for hot fire acceptance test. The tests outlined in Table 5-1 were conducted at propellant inlet pressures of 350,225, and 100 psia. A simulated altitude of greater than 100,000 feet was maintained throughout all testing. Measurements included thrust (F), chamber pressure (Pc), propellant inlet pressure (Pinj), steady-state propellant flow rate (m), and pulse mode propellant consumption (/mdt).

Sequence	On Time (msec)	Off Time (msec)	No. of Pulses
а	20	980	100
b	20	480	100
с	50	950	100
d	50	450	100
е	100	900	100
f	150	850	100
g	10 sec	Steady-State	1

Table 5-1. Acceptance Test Duty Cycle

Prior to initiation of testing, the RHU's were installed and the engine held at vacuum (120,000 feet) overnight. The chamber temperature, with no insulation, stabilized at 115°F. A wrap of microquartz insulation was then installed around the chamber casting, leaving both ends uninsulated, and again left at vacuum overnight. The equilibrium temperature was 155°F, in an environment of approximately 60°F. Adding free convection (air at 120,000 feet altitude) to the thermal model, and using appropriate insulation properties, yielded predictions of 120°F and 180°F for the above conditions. Additional refinement of the model is required to accurately predict the catalyst bed temperature in space, but the above data yield confidence that the 200°F goal would be exceeded in high vacuum (10<sup>-5</sup> torr). An electric radiant heater was then added as shown in Figure 5-1 to supplement the RHU's and maintain 210<u>+</u>10°F at the initiation of every test.

No specific accept/reject criteria were established for this test. It was intended, however, to verify that the engine would repeat the operating characteristics of trh development thrusters. It was also intended to simulate a flight type application where the launch environment would follow an acceptance hot fire test. Data from this test sequence are presented in Section 5.3.



Figure 5-1. Photo of RCHE on Test Stand

Following the hot fire test, the propellant valve was removed from the engine assembly, flushed with Isopropyl Alcohol (IPA), and vacuum dried. The engine was then re-assembled in preparation for a vibration test.

### 5.2 VIBRATION TEST

A vibration test was planned to simulate the effects of a launch environment on the catalyst bed. The exposure, as presented in Table 5-2, is representative of a flight qualification vibration exposure. Figures 5-2 and 5-3 show the RCHE mounted on the test fixture in preparation for the first (X-X) axis test. The engine was subjected to the random and sine vibration exposures in this axis, after which the fixture was rotated 90° (to the Y-Y axis) and the exposure repeated. During the random vibration exposure, however, the valve inlet tube separated from the valve. Tape was placed over the opening, to minimize particulate contamination, and testing in this axis completed. The fixture was then mounted for vibration in the vertical (Z-Z) axis to complete the vibration exposure. Accelerometer data from these tests are presented in Figures 5-4 to 5-9.

## Table 5-2. Vibration Spectrum

Random Vibration About three orthogonal axes: Flat from 300 to 1200 cps at 0.25 g<sup>2</sup>/cps Roll up to 300 cps at 3 db/octave Roll off above 1200 cps at 6 db/octave Integrated load - 19.5 g rms Test time - 180 seconds/axes Sinusoidal Vibration About three orthogonal axes: Sweep at spectrum of 5 to 2000 cps at a rate of 2.0 minutes per octave at a level of 1.0 g (zero

to peak)



101896-73



Figure 5-2. Vibration Test Setup



101897-73

Figure 5-3. RCHE on Vibration Fixture







Figure 5-5. Accelerometer Data - X-X Sine















Figure 5-9. Accelerometer Data - Z-Z Sine

Examination of the valve inlet and separated inlet tube revealed that the tube had fractured. The tube had been EB welded to the end plate of the valve from the back side, and the fracture appeared to occur at the bottom of the weld penetration. This is deemed a minor problem with the valve which would readily be correct for any future application. TIG welding was then utilized to re-attach the valve inlet, maintaining an argon purge and minimizing heat input to the valve.

Proof pressure and internal and external leakage tests were then successfully completed, verifying that the unit was ready to continue the test program.

5.3 DUTY CYCLE DEMONSTRATION

The engine was installed on the thrust stand as for the acceptance test, including the radiant heater and  $GN_2$  coolant purge. Vacuum was attained and then maintained continuously for 9 weeks, 2 weeks beyond the end of the duty cycle. The planned duty cycle was as presented in Tables 5-3 and 5-4, with every test sequence to start at 210 ±10°F. As indicated in Table 5-4, digital data was scheduled to be acquired at approximately 25,000 pulse increments and/or every 50 ambient starts.

The test was conducted essentially as planned, except that 37 extra ambient starts were accumulated. Minor problems with the data acquisition system and/or other test problems resulted in repeating certain tests. Tests were added at the start, middle, and end of the duty cycle to obtain oscilloscope photographs of pulse sweeps. The total accumulated life on the engine is summarized in Table 5-5.

	- 2 - 5	DUTY CYCLE A	
Sequence*	On Time (msec)	Off Time (msec)	No. of Pulses
а	20	980	100
Ъ	20	480	100
c	50	950	100
d	50	450	100
e	100	900	100
f	150	850	100
g	10 sec	Steady-State	1

# Table 5-3. Duty Cycle Definitions

\*Propellant feed temperature is 40°F +5°F

DUTY CYCLE B

Sequence*	On Time (msec)	Off Time (msec)	No. of Pulses
а	20	980	500
Ъ	20	480	500
с	50	950	500
d	50	450	500
e	100	900	500
£	150	850	500
g	l min	Steady-State	1
		DUTY CYCLE C	
Sequence*	On Time (msec)	Off Time (msec)	No. of Pulses
а	100	900	1000
b	10 sec	Steady-State	1

\*Propellant feed temperature is 40°F ±5°F

Tist No.     (Table 4-B)     100     235     330     Americi Signity     Licks     Licks <thlicks< th="">     Licks     Licks</thlicks<>		DUTY CYCLE	STATIC	FEED PRESS	SURE (PSIA)	CUMULE	Tive	
1     10     ecc     teacht-riste     x     x     x     x     y     b00       2     A     x     x     x     x     y     b00     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x     x	TEST NO.	(Table 4-8)	100	225	350	Ambient Starts	C.cles	DIGITAL
2 A x x 10 564   3 8 x 11 10 564   3 8 x 1 10 564   4 1 x x 1 166   5 8 x 1 10 569 x   6 8 x x x 10 569   7 10 10 10 10 10   6 8 10 10 10 10   7 8 10 10 10 10   8 8 10 10 10 10   9 10 10 10 10 10   9 10 10 10 10 10   9 8 10 10 10 10   10 8 10 10 10 10   11 8 10 10 10 10   11 8 10 10 10 10   11 8 10 10 10 10   11 8 10 10 10 10   11 8 10 </th <th>-</th> <th>10 sec steady-state 10 sec steady-state 10 sec steady-state</th> <th>×</th> <th>×</th> <th>×</th> <th>- ~ E</th> <th>- ~ ~</th> <th><b>ч</b> ч ч</th>	-	10 sec steady-state 10 sec steady-state 10 sec steady-state	×	×	×	- ~ E	- ~ ~	<b>ч</b> ч ч
3 8 x x 1 460 x   4 C x x 1 11,810 x   5 Repeat Text No. 4, 8 times x x 11,810 x   7 Repeat Text No. 4, 8 times x x x 11,810   8 Repeat Text No. 4, 9 times 105 99 31,836 x   9 Repeat Text No. 4, 9 times 129 20,654 x   10 Repeat Text No. 4, 9 times 129 20,661 x   11 Repeat Text No. 4, 9 times 200 81,661 x   11 Repeat Text No. 4, 9 times 201 81,661 x   11 Repeat Text No. 4, 9 times 201 81,661 x   11 Repeat Text No. 4, 9 times 201 81,661 x   11 Repeat Text No. 4, 9 times 201 91,502 x   12 Repeat Text No. 4, 9 times 201 91,502 x   13 Repeat Text No. 4, 9 times 201 91,502 x   14 Repeat Text No. 4, 9 times 201 91,502 x   13 Repeat Text No. 4, 9 times 201 91,502 x   14 Repeat	2		-	-	н	10 17 24	604 1205 1806	* * *
4   C   x   x   x   y   11,810     5   Repeat Test No. 4, 8 times   x   y   y   13,811     7   Repeat Test No. 4, 8 times   y   y   y   y,816   x     7   Repeat Test No. 4, 8 times   y   y   y   y   y,816   y     9   Repeat Test No. 4, 9 times   y   y   y   y   y,936   x     10   Repeat Test No. 4, 9 times   y   y   y   y   y,936   x     11   Repeat Test No. 4, 9 times   y   y   y   y   y,969   x     11   Repeat Test No. 4, 9 times   y   y   y   y   y   y     11   Repeat Test No. 4, 6 times   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   y   <	~		×		*	31 38 45	4807 7858 10,809	
5     Repeat Test No. 4, 8 times     9     37,836     x       7     Repeat Test No. 4, 4 times     105     40,639     x       7     Repeat Test No. 4, 4 times     129     24,654     r       8     Repeat Test No. 4, 9 times     150     54,654     r       9     Repeat Test No. 4, 9 times     204     81,681     x       10     Repeat Test No. 4, 9 times     210     99,699     x       11     Repeat Test No. 4, 5 times     210     99,699     x       12     Repeat Test No. 4, 5 times     210     99,699     x       13     Repeat Test No. 4, 6 times     210     99,550     x       14     Repeat Test No. 4, 8 times     331     121,523     x       15     Repeat Test No. 4, 8 times     331     121,520     x       17     Repeat Test No. 4, 17 times     331     121,533     x       18     Repeat Test No. 4, 17 times     332     140,550     x       13     Repeat Test No. 4, 17 times     332     142,511     x<	-		ж	-	-	49	11.810 12.811 13.612	
7   Rupeat Text No. 4, 4 times   1.9   2.4.651     8   Rupeat Text No. 2   150   54.654   n     9   Rupeat Text No. 4, 9 times   150   54.654   n     10   Rupeat Text No. 4, 9 times   2004   81.681   n     11   Rupeat Text No. 4, 5 times   210   84.684   n     12   Rupeat Text No. 4, 5 times   240   99.699   n     13   Rupeat Text No. 4, 6 times   230   119.520   n     14   Rupeat Text No. 4, 6 times   331   122.523   n     15   Rupeat Text No. 4, 8 times   337   149.550   n     16   Rupeat Text No. 4, 7 times   357   149.550   n     17   Rupeat Text No. 4, 7 times   357   149.550   n     18   Rupeat Text No. 4, 7 times   357   149.550   n     19   Rupeat Text No. 4, 7 times   357   149.550   n     20   Rupeat Text No. 4, 2 times   356   145.533   n     21   Rupeat Text No. 4, 2 times   357   149.550   n <th>ور در</th> <th>Repeat Test No. 4, 8 times Repeat Test No. 4</th> <th></th> <th></th> <th></th> <th>66 201</th> <th>37.836 40.839</th> <th>-</th>	ور در	Repeat Test No. 4, 8 times Repeat Test No. 4				66 201	37.836 40.839	-
9 Repeat Test No. 4, 9 times 204 81,681 x   10 Repeat Test No. 4, 5 times 210 84,681 x   11 Repeat Test No. 4, 5 times 210 99,699 x   12 Repeat Test No. 4, 6 times 261 101,502 x   13 Repeat Test No. 4, 6 times 261 101,502 x   13 Repeat Test No. 4, 6 times 237 119,520 x   14 Repeat Test No. 4, 6 times 351 149,550 x   15 Repeat Test No. 4, 1 times 351 149,550 x   17 Repeat Test No. 4, 7 times 372 149,550 x   18 Repeat Test No. 4, 7 times 376 151,353 x   20 Mepeat Test No. 4, 7 times 376 153,550 x   17 Repeat Test No. 4, 7 times 376 153,550 x   18 Repeat Test No. 4, 7 times 376 153,550 x   20 Mepeat Test No. 4, 2 times 376 153,550 x   21 Repeat Test No. 4, 2 times 376 153,550 x   22 Repeat Test No. 4, 2 times 236,010 376,010 x   23 Repeat Test No. 4, 2 times <th>~</th> <th>Repeat Test No. 4, 4 times</th> <th></th> <th></th> <th></th> <th>129</th> <th>54.654</th> <th>-</th>	~	Repeat Test No. 4, 4 times				129	54.654	-
11 Repeat Test No. 4, 5 times 240 99.699 x   12 Repeat Test No. 2 261 101.502 x   13 Repeat Test No. 4, 6 times 297 119.520 x   14 Repeat Test No. 4, 6 times 297 119.520 x   15 Repeat Test No. 4, 6 times 351 146.547 x   16 Repeat Test No. 4, 8 times 357 149.550 x   17 Repeat Test No. 4, 9 times 372 149.550 x   19 Repeat Test No. 4, 9 times 372 145.547 x   19 Repeat Test No. 4, 9 times 420 172.374 x   20 Repeat Test No. 4, 9 times 420 172.374 x   21 Repeat Test No. 4, 9 times 420 172.374 x   22 Repeat Test No. 4, 9 times 52 206.010 x   23 Repeat Test No. 1, 9 times x 420 172.374 x   24 Repeat Test No. 4, 9 times 22 206.010 x   23 Repeat Test No. 4, 9 times 22 206.010 x   23 Repeat Test No. 4, 9 times x 22 206.010	e e o	Repeat Test No. 4, 9 times Repeat Test No. 4,				204	81,681 84,684	
13 Repeat Test No. 4, 6 times 297 119,520 x   14 Repeat Test No. 4, 6 times 303 122,523 x   15 Repeat Test No. 4, 8 times 351 146,547 x   17 Repeat Test No. 4, 7 times 357 149,550 x   18 Repeat Test No. 4, 7 times 378 151,353 x   19 Repeat Test No. 4, 7 times 378 151,353 x   20 Repeat Test No. 4, 7 times 420 172,374 x   21 Repeat Test No. 4, 9 times 420 172,374 x   22 Repeat Test No. 4, 2 times x x 206,010 x   23 Repeat Test No. 4, 2 times x x x x		Repeat Test No. 4, 5 times Repeat Test No. 2				240 261	99,699 101,502	
15 Repeat Tast No. 4, 8 times 351 146,547 x   17 Repeat Tast No. 4 8 times 357 149,550 x   19 Repeat Tast No. 4, 7 times 378 151,353 x   19 Repeat Tast No. 4, 7 times 420 172,374 x   20 Repeat Tast No. 4, 9 times 420 172,374 x   21 Repeat Tast No. 2, 2 times x x x   22 Repeat Tast No. 1, 9 times x x x   23 Repeat Tast No. 1, 9 times x x x   21 Repeat Tast No. 1, 9 times x x x   21 Repeat Tast No. 1, 9 times x x x   23 Repeat Tast No. 1 x x x	24	Repeat Test No. 4, 6 times Repeat Test No. 4				297 303	119.520	н
17 Repeat Test No. 2 376 151,353 x   18 Repeat Test No. 4, 7 times 420 172,374 x   19 Repeat Test No. 4, 9 times 420 175,374 x   20 Repeat Test No. 4, 9 times 420 175,377 x   21 Repeat Test No. 1, 2 times 480 202,404 x   21 Repeat Test No. 1, 2 times x x x   22 206,010 x x x   23 Kandora test No. 1 x x x	22	Repeat Test No. 4, 8 times Repeat Test No. 4				351 357	146,547 149,550	×
IB     Repeat Test No. 4, 7 times     10. 4, 7 times     420     115,377     x       19     Repeat Test No. 4, 9 times     426     115,377     x       20     Repeat Test No. 4, 9 times     480     202,404     x       21     Repeat Test No. 1, 2, 2 times     522     206,010     x       21     Repeat Test No. 1     52     206,010     x       23     Repeat Test No. 1     x     x     206,013     x	17	Repeat Test No. 2				376	151,353	•
20     Repeat Test No. 4, 9 times     480     202,404       21     Repeat Test No. 2, 2 times     522     206,010     x       22     Repeat Test No. 1     x     525     206,013     x       23     Repeat Test No. 1     x     x     526     206,016     x       31     KG Sec. steedv-state     x     x     526     206,016     x	81	Repeat Test No. 4, 7 times Repeat Test No. 4				420	112.374	
	20 21 22	Nepeat Test No. 4, 9 times Nepeat Test No. 2, 2 times Nepeat Test No. 1 60 Sec. steadvistate	×	×	×	480 522 528	202,404 206,010 206,013 206,016	жжж

Table 5-4. Rocket Engine Assembly Demonstration Test Duty Cycle

#### Table 5-5. Engine Test Summary

Total	Ambient (200°F) Starts	566
Total	Pulses	210,098
Total	Steady-State	2,646 seconds
Total	ON Time	23,941 seconds
Total	Propellant Thruput	431 pounds

Engine performance at the beginning and end of the duty cycle is summarized in Figures 5-10 through 5-13. The thrust shift which resulted from the duty cycle test is nominally 15% and 27% at high and low propellant inlet pressures respectively. Thrust level and ISP versus life are presented in Figures 5-14 and 5-15 for three inlet pressures, and Figures 5-16 and 5-17 summarize pulse mode life trends. A second order, least squares fit, was used to curve fit the data. Additional data are presented in Appendices A and B. The specific test sequence and the data obtained are tabulated and plots presented where applicable.

Typical characteristics of the engine at the start, middle, and end of the duty cycle are shown via oscilloscope photos in Figure 5-18. The pressure overshoots, which appear at the end of the duty cycle, started occurring on a few pulses during the warmup transient after approximately 100 ambient starts. After nearly 500 ambient starts, random pressure overshoots occurred after thermal equilibrium had been attained. The frequency of the overshoots increased until they occur on nearly every pulse. It is noteworthy that even though the pressure overshoots are occurring, the slope of the life plots at the end of the duty cycle indicate much greater life capability still remaining.

In parallel with the RCHE effort, TRW fabricated and tested an unheated IR and D thruster of the RCHE design (less RHU ports). All starts on this engine were controlled to  $70^{\circ}F \pm 20$ , and only chamber pressure data were obtained. The overall shift in performance characteristics at the end of the duty cycle is essentially the same as the RCHE. The analog data. as summarized in Figure 5-19, revealed fewer pressure overshoots, of lower magnitude, of the duty cycle, however.







Figure 5-11. Steady-State Specific Impulse vs Inlet Pressure







Figure 5-13. Pulse Centroid vs Inlet Pressure















Data shown at 350 psia inlet pressure

Tests shown consist of a 10 second steady-state firing (first picture) followed by a single test varying the pulse width (on time) from 0.150 to 0.020 second on (second picture) and then from 0.020 to 0.150 second on (third picture) at a constant pulse rate of one per second. Five pulses at each pulse width are shown in each picture.



### Data shown at 350 psia inlet pressure

Tests shown consist of a 10 second steady-state firing (first picture) followed by a single test varying the pulse width (on time) from 0.150 to 0.020 second on (second picture) and then from 0.020 to 0.150 second on (third picture) at a constant pulse rate of one per second. Five pulses at each pulse width are shown in each picture.

### 6. POST TEST EXAMINATIONS

Post test condition of the RCHE was evaluated via weight, X-ray, and disassembly of the thrust chamber. The IR and D thruster condition was similarly evaluated.

The quantity of catalyst loaded in the engines was 20.6 grams in the RCHE and 20.2 grams in the IR and D engine. The measured weight change of the assemblies, post versus pre-test, was 1.7 and 2.6 grams, respectively. This translates to 8 percent catalyst loss for 'he RCHE and 13 percent for the unheated IR and D engine.

Examination of the X-rays of the two engines yields results consistent with the weight data. X-rays of the RCHE were somewhat limited due to the mass of the RHU ports, but did show that the catalyst bed was relatively intact. No voids were evident, nor was any deformation of screens. The IR and D thruster X-rays, however, indicate some catalyst loss from the upper catalyst bed.

Electric-discharge machining (EDM) was chosen for disassembly of the RCHE to minimize vibration of the catalyst bed. Isopropyl Alcohol was used as the dielectric fluid for this operation so that any fluid contacting the catalyst could be readily removed. A circular cut was made through the headplate, between the outer periphery of the headscreen and the weld joint to the chamber wall. After the cut was made, the injector and upper catalyst bed were removed. The lower catalyst bed was vacuum dried before removal, however, to eliminate residual alcohol.

The catalyst bed was found in relatively good condition. Some fines were present, but there was no indication of voiding, severe compaction or sintering. All of the catalyst was removed by inverting the chamber and lightly tapping it with a pair of tweezers. Some catalyst was found in the headspace. A hole had formed in the headscreen, apparently allowing penetration of the catalyst. The quantity was very small, however, filling only 10 to 15 percent of the volume and may have entered the headspace after the test. A fracture of the midscreen also occurred, along with a separation of the weld over about one-third of the circumference. The screen had curled toward the injector after fracturing and was thus close enough to the headscreen that it may have been in contact.

A view of the injector, through the hole in the headscreen, is shown (as first removed from the RCHE) in Figure 6-1. This unusual appearance was first interpreted as severe nitriding of the injector, with flakes from inside the flow passage partially blocking the injector orifices. Water flow, however, showed no change in flow characteristics, and the water dissolved and/or removed the deposit responsible for the flakey appearance, leaving the injector as shown in Figure 6-2. A similar appearing deposit results from evaporating the alcohol used as the dielectric for EDM, leaving the metallic particles resulting from the cut. The appearance in Figure 6-1 is thus attributed to this type of deposit from the disassembly operation.



Figure 6-1.RCHE Injector UponFigure 6-2.RCHE Injector PostDisassembly (20X Size)Water Flow (20X Size)

The test data were further analyzed to assess the possibility that the above deposit was not from the EDM process, was in-soluble in hydrazine (though soluble in water) and had affected the engine performance. This evaluation showed that the increase to the total pressure drop (thus the thrust shift) was essentially a linear function of flow rate, yielding the conclusion that the thrust shift is the result of increasing catalyst bed pressure drop. Had the shift been due to the injector, it would relate to flowrate squared. The IR and D thruster was disassembled by making a circumferential cut in the chamber shell slightly below the headplate. During removal of the headplate it was noted that the catalyst bed had settled approximately 0.1 inch below the headplate, indicating about 7% loss of catalyst volume. The condition of the catalyst bed was very similar to that of the RCHE except for the greater loss and, accordingly, a somewhat greater quantity of catalyst fines in the lower bed.

This headscreen also had numerous broken wires with some pieces missing. Figure 6-3 shows the IR and D headscreen and Figure 6-4 shows the RCHE headscreen. A section through one of the headscreen wires is shown in Figure 6-5, showing the nitride penetration along the grain boundaries. The large grain size, relative to the wire diameter, and the nitride penetration result in an extremely brittle and weakened condition. Both the injector and the headscreen retainer exhibited a nitride layer of nominally .001 inch, with much deeper penetration along the grain boundaries. A section through a web of the headscreen retainer is shown in Figure 6-6, midway through the thinner (.020 inch) demension. Nitride penetration along grain boundaries had also occurred here, but the relative size of the grains to the part is such that structural adequacy retained.





Figure 6-3. IR&D Headscreen

Figure 6-4. RCHE Headscreen







Figure 6-6. Section through Headscreen Retainer (50 X)

The RHU's were also inspected after the test. They were first removed from their graphite reentry members and visually inspected. There was no apparent damage to the outer surface of the Pt-Rh clad. A test was then conducted to verify that the pressure relief device was releasing the helium generated by the radioisotope decay of the fuel. Each assembly was placed separately into a vacuum chamber which was then connected to a Veeco helium leak detector. The chamber was then evacuated and the helium flow measured. Data recorded during this series of tests are noted in Table 6-1.

Unit	Helium Permeation Rate (Std cc/sec)
S/N 234	$3.4 \times 10^{-7}$
S/N 235	$1.1 \times 10^{-7}$
S/N 236	$2.0 \times 10^{-7}$

Table 6-1.

The helium flow rates recorded indicate that the pressure relief devices are functioning properly.

Post-test sealed source radiography studies were performed to verify the integrity of the capsule components including the radioisotope fuel pucks. Each heat source was exposed to a 2 curie, Cesium-137, sealed source for a period of thirty minutes. The radiographs showed no indication of damage or failure of any of the capsule components. However, one fuel puck, loaded in RHU S/N 235 appeared to be cracked circumferentially resulting in a complete break. A portion of this puck also appears to be fractured at one end.

In conclusion, the RHU's appear to be integral and are functioning normally. The fractured puck in unit S/N 235 does not affect the integrity or function of these heat sources. A smear survey and direct reading alpha radiation monitor detected no evidence of fuel contamination.
## 7. RELIABILITY AND MAINTAINABILITY

The formal demonstration of specific reliability levels and maintainability characteristics was not a goal of the Integrated Radioisotope Catalytic Monopropellant Hydrazine (RCHE) advanced technology program. However, attainment of the required program goals did require a large number of engine ambient starts and pulses on slightly varying engine configurations even through a large amount of firing time was not generated. The successful completion of a large number of engine ambient starts and pulses on very similar configurations does indicate what reliability levels could be expected from a production program where field utilization missions require a large number of ambient starts and pulses.

Figure 7-1 shows the program test history. All configurations considered similar enough to be representative of the selected configurations for the purposes of reliability evaluation are indicated. Two (2) malfunctions occurred during the applicable engine runs. Both of the malfunctions can be discounted as not chargeable to the engine. One Malfunction (failure at the chamber pressure tap) was a side effect of the goals and practical methods used to make the many hardware changes required during that early phase of the program. This element is an in-process test appendage only that would have no impact on flight hardware. The second failure (valve inlet tube separated from the valve) occurred during vibration testing and is chargeable to the valve and not to the engine. In all the testing only the failure at the chamber pressure tap which occurred early in the development program caused premature shutdown of the engine. The data applicable to reliability evaluation shown on Table 7-1 can be summarized as follows:

TOTAL PROGRAM APPLICABLE DATA FOR RELIABILITY EVALUATION:

- Total pulses accumulated on all hardware representative 1,230,241 of the final design
- 2. Total ambient starts accumulated on all hardware 626 representative of the final design.
- 3. Total pulses accumulated on the final design hardware 210,000 unit without repair/refurbishment.
- 4. Total ambient starts accumulated on the final design 566 hardware unit without repair/refurbishment.

5. Total failures experienced on all hardware 1 representative of the final design.

0

 Total chargeable failures experienced on all hardware representative of the final design.

No chargeable failures in 626 ambient engine starts demonstrates an ambient engine start probability of 0.9950 at a 95% confidence level based on binomial sampling techniques. Likewise, no chargeable failures in 1,230,241 engine pulses demonstrates an engine pulse probability of 0.99999 at a 95% confidence level. Data is not sufficient to make a numerical life expectancy calculation on a single hardware item (i.e., A RCHE is good for 500,000 pulses at a reliability level of  $X_1$  at a confidence level of  $Y_1$  or, a RCHE is capable of 1,000 ambient starts at a reliability level of  $X_2$  at a confidence level of  $Y_2$ .) However, condition of the RCHE at teardown after extensive duty cycle testing indicated useable life remaining.

The RCHE is essentially one-piece construction with only the valve being easily removed for maintenance. The following welds are made:

Resistance-welds

Catalyst retainer plate and screens as part of the catalyst loading operations.

EB Welds

Injector assembly (injector, headscreen, and headscreen support) to chamber.

However, the only time dependent (degradating) components on the RCHE other than the valve which can be removed for maintenance are the O-ring seal used for the valve/injector feed tube interface and a Voi-Shan soft seal used at the valve inlet. Therefore, any maintenance required (other than the Valve) is likely to be as a result of usage rather than periodic maintenance required because certain parts have passed their storage capability.

PI	OGRAN PHASE/HARDWARE CONFIGURATION	TYPE OF MI TEST AJ	NOER OF PULSES ID ANDIENT STARTS	ALLOWABLE DATA FOR RELIABILITY EVALUATION	FAILURES/CHARGEABLE FAILURES	CONNENTS
The	star Davelopment					
A.	Baseline 5-16 thrust	Not-Firing	"A large number	No	+0/0	Selected 18 to 20 much catalyst for the
A-1	Engine. Bolt-up thruster com- figuration allowing parametrical evalua- tion of vatiations of injector, handacreen, and catalyst mesh size for the upper catalyst bed.	Tests	of pulses were accumulated but not formally recorded.			upper bed.
A-2	Pinal injector/upper catalyst bed configu- rations per A-1. Evaluations of varia- tions to lower catalyst bed.	Accelerated Life Teste	83,600 pulses (0.020, 0.050, 0.100, and 0.150 second on times at "4 pulses per seco	)) nd.	•1/0	Used 20 to 30 mesh catalyst for lower bed. Disasembly revealed deformation of the headscreen.
			134,740 pulses (0.020 0.050, 0.100, and 0.1 second on times) at pulses per second.	50 4	0/0	Used 18 to 20 mesh catalyst for lover bed. Disassembly revealed deformation of the headscreen.
A-3	Headscreen Evaluation Tests. Added head- screen retainer and designed two alter-	Special Accelerated Life Testa				Haadacreens vere changed from 40X40 mesh, .009 vire diameter to 30X30 mesh, .010 vire diameter.
	ware injectifs.	Injector 7	80,000 pulses	No	0/0	40 mesh headucreen.
		Injuctor E		50	0/0	
		Injector D	80,000 pulses	Yes	0/0	40 mech headscreen
			280,000 pulses	Yes	0/0	30 mesh headacrean 30 mesh headacrean
			280,000 pulses	Yes Yes	0/0 0/0	30 mesh headscreen with retainer 30 mesh headscreen with retainer
Tine (1) (2) aged for safe	D'alga 1 design features: Configured for opti- injector/catalyst bed, RHU's integrally pack- , (3) Improved capsule earth orbit nuclear ty.	Acceptance Tests Proof Pressure Test. Leak Te (external/in- ternal (valve) Not Fire Test	net 0 1803 (including	Yes Yes	0/0	
		Vibration	21 ambient starts)	Yes	1/0	Walna falsa sub- anaratad dara aba untur
		Proof Pres- sure Test. Loak (anter- mal/internal (Valve) Test.	0	Yes	0/0	These tests (Proof Pressure and Leakage) required to verify fix of valve inlet tube failure
		Duty Cycle Demonstra- tion.	210,090 pulses (including 563 ambient starte)	Yee	0/0	Life plots of test data indicate much greater life capability remaining. Post test examination showed: A 3% catalyst loss, the catalyst bed vas relatively intact, no voids evident, no deformation of screens, catalyst bed in good condi- tion, few fines present, no indication of voiding, savers compaction or sintering a hole was found in the headscreen, mid- erceen fractured, and separation of the weld over about 1/3 of the circumference.
			TOTAL PROGRAM APPLICA	BLE ALLOWABLE DATA	POR	
			L. Total pulses accu	mulated on all hare	lware 1.230.241	
			2. Total ambient sta	the final design of accumulated on	all <u>626</u>	
			3. Total pulses accu hardware unit wit	mulated on the final mulated on the final chout repair/ret.rb:	l design	
			<ol> <li>Total ambient starts accumulated on the</li></ol>			
			5. Total failures en	the final dealer	rdvere 1	
			<ol> <li>Total chargaable all hardware repr design</li> </ol>	failures experience esentative of the f	d on inal	
		"The goals of thruster pulse many variation tion phase ser the goals of t in excess of w probable that contributed to sidered non-ch	the thruster developme accumulation. The th a to obtain the optimu oppace hardware handli his phase of the progr hat would be experience the failure of the cha by the accessive roug argeable to the basic	nt program in this rusters were tested m injector, hesder ng procedures would sm. The hardware t ed in a qualificati mber pressure tap d h handling it had e design.	phase were not conduciv , changed elightly and een, and cattlyst mash have been inefficient herefore was subjected on or production progra wing the Accelerated 1 xperienced. Therefore,	ve to the tracking of tested again through eise. Normal produc- and a hinderance to to handling abuse far m. It is highly .ife Tests was at least , this failure is con-

Figure ?-1. Test/Failure Program History

## 8. CONCLUSIONS

This program successfully demonstrated the integration of radioisotope heat sources into a catalytic hydrazine engine. Over 210,000 pulses were accumulated, with 565 "ambient" temperature starts and with indications of much greater life capability. Comparison of the test results of 200°F versus 70°F "ambient" starts indicates that to the extent of the test conducted, the headspace type thruster performance is not sensitive to the difference. Post test hardware condition, however, reveals greater catalyst attrition in the 70°F engine. Had the test been more extensive, therefore, the heated engine would most likely demonstrate a greater ultimate life capability.

Nitriding of the Haynes Alloy 25 (L605) headscreens and midscreens yielded several broken wires in both engines. Nitriding of other elements of the engine was less severe and no material problems are anticipated for much more extensive duty cycles. A material change is recommended for the screens, however, to increase the life capability.

Both 5-pound engines demonstrated less sensitivity to ambient temperature starts than other existing TRW flight qualified designs. The mode of degradation with life is also consistent, showing a gradual increase in catalyst bed pressure drop yielding a reduced thrust level. APPENDIX A ADDITIONAL TEST DATA



























































A-26










A-31





































A-49







APPENDIX B ENGINE TEST LOG ENGINE TEST SUMMARY RCHE S/N ROOT A CC E P T A N C E

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	5 UNMARATION	AMBIENT STARTS	-	2			5		*	,	4	ø	11	11	13	M	15	14	17	1	N	2	12	77	67	N	15	27	12	20	14	
NON LANNAU	2	SAGI LANI	. 2405	5416	1001	. 9462	1.0141	1.02%	1. C#13	1640.	11011	. 2535	1.4053	1.49.19	1+52.1	2.1440	2.4211	2.4497	2.5125	216415	2.7400	2.9772	9. 40/4	5. 5123	1045.6	3.5042	3.4616	9. 7461	S. BOW	4.10.64	16271	
Canada-	NON	NO NO NO	1.01	0.12	52.9	64.5	5//3	51.6	6.13	6.35	9.9	79.9	6.4.	24.9	1.7.6	101.9	12.0	14.0	114.0	21.2	242	2.0%	121.2	142.0	14.0	144.0	21.0	(74.D	10.00	0402	2.11.2	T
1	-mm	141	10	21.0	2.5	19.4	1	1	1	1	1	1	1	1	1	1	1.4	1	1	1	1	1	1	20.2	1	1	1	1	1	1	6.4	T
	1 34		12	3.6	88	0.1	1	1	1	1	1	1	1	1	1	1	2.0	1	1	1	1	1	1	11	1	1	1	1	1	1	9.5	Π
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		(UBP)	5.71	5.71	4.24	2.31	1	1	1	1	1	1	1	1	1	1	5.70	1	1	1	1	1	1	4.26	1	1	1	1	1	1	2,23	
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	-	TIMP.	212	211.1	1402	24.4	1.5.11	122	216	216	186	2195	245	2/8	197	797	271.5	30	216	207	216	216	216	211.5	216	197	216	221	216	210	21.2	
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<sup>1</sup> PC ROUGHNESS DETERMINED FROM MITA BETWEEN 8 AND 10 SECONDS 2 40.45 OVERSHOOT AT APPROX. 15 SECONDS

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URMMAT FOIL	DF LLANT	(IBM)	28.58	28.93	30.13	30.88	31.05	32.94	33.11	35.01	35.17	37.07	37.24	39,13	39.30	41.20	41.57	93.26	43,93	46.33	99.24	92.39	47.56	29.45	49.62	51.52	51.68	53,58	55:22	55.65	55.81	57.71	57.98	59.78
-MMA	ZON	(C)	136.4	\$27.4	57.3	603	70.3	70.2	2.08	1'01	1.06-	0.041	0.000	6.699	6.900	109.8	8.911	219.7	229.7	329.6	339.6	435.5	5.204	545.4	4:555	655.3	665.3	7652	775.2	875.1	885.1	985.0	D'966	6.460
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Max         Max <td>1</td> <td>Sav L</td> <td>6</td> <td>2</td> <td>ALL DAY</td> <td>-</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>2</td> <td>1</td> <td>10.0</td> <td>-</td> <td>-</td> <td></td> <td></td> <td></td> <td>11</td> <td>13 167</td> <td>10.6 2.96</td> <td>44</td> <td>370</td>	1	Sav L	6	2	ALL DAY	-										2	1	10.0	-	-				11	13 167	10.6 2.96	44	370
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	MILLAND ICH	5.24	225	1.92	234	8.92	868	9.05	61.6	532	9.60	9.99	0.22	12.0	0.32	0.43	0.54	0.73	26.4	801	1.27	1.47	160	1.86	551	2.18	2.27	15.5	16.6	6.31	14.47	13.57
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	NO NO	- 1714	- 17245	W725	- 1735	31734	136	- 1731	1734	1738	- 1739	- 1740	S 1741	1741)	- 17415	- 17424	- 1792	- 1745	2011	SINGE	1744	- 1796	- 17673	1747	842-	1750	3 1751	11751	- 1762	1111	1 1773	- 1785
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	INTROID MALO MALO	16.9	10	1	44.0	1	40	14.6	340	50.5	0.0	112.3	1	34.2	8 6	54.4	30.6	1	1	1	1	1	1	1	151 8		-	1	1	1		
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	PULSE 1-5	A 525	1		3.616	1	1.430	1.811	A.1.H	3.750	6.050	1.13	1	- 18-1	.9923	2.812	2.004	1	1	1			1	-	3.49				1	1		
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# EAN OUT OF FUEL

F		F			PULLE MODE	CHARACTERNIETS				STEADY ST	AUT CHARACTER	5165		Connect Science	MAT KON	
1.11	SAMK PRESS	INU. PARTIN.	2	CHAMBER PULST	PRESSURE INTEGRAL VACUUM	The second secon	The Charlen	TANT TANK	THE DUE A	NULL PLAN	Sercing B	No. 1	NAME OF COLOR	CF ON PROP	SULAND OF SU	BAR NI
Ow 11MG	N.M.	-			32 2.1 001-02		1	N.84 012	1	1		-	1	144.7 386	12 4	173
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1-10 34	104		1				1	210 11-18		1		-	1	222939 90	2.63	483
840 24	7 46		442	10.110				210	- 10.0	1			22252	223059 40.	1 80	490
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8-40 14	16770		144	/an/706			1	1 00	- 10.0	1		-	164.22	1.112 8 404	4.56	492
0.00	11 234		000	and and				210 1:58	- 15	1	-		1	225.47 400	6.76	493
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F20 34	Ea1 103	-					-	210 1254	1 3	T		-	1	27472 6 40	1.93	495
6-20 31	386	-	277	201794			1	1 07	0.01 -	1	-	-	-1259-2	12625 90	653	496
8-21 30	125 00		-	- the second				210 210	1	1		-	1	12132 - 414	0.59	497
8-21 31	657 24		222	100/100				20	100	1			- 2265 -	12953 901	301	498
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	MULANCE Col	157	647	690	153	170	1 76	1 82	143	206	2 50	266	2 2 2	58 7	2 94	3.04	214	1.2.3	125	3.78	3.31	385	392	4.00	2.13	431	9.08	4 54	9.62	9.68	08.0	1.93	5.17
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	114401 114401 114100	210	210	200	24	210	200	216	117	225	20	209	225	224	220	220	225	223	222	206	207	205	6/2	216	209	213	210	222	210	207	210	274	Sor
	MBOID CONT MARCO	1		1	1	1	2.2	1.1	1.1	55.0	1.1	104.0	1	15.51	43.4	57.6	6:53	9.7.8	14.9	T	2.6	995	8.0	20.9	39.6		1	96.0	+	3.2	1.7	1 0	SCAP 1
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	PLISSURE PLISSURE 20-100	1	1	1	1	1	2.162	2.250	4.425	5.502	10.19	15.02		1.654	1.703	3939	4.007	7.674	11.41		1655	1538	2 521	2.313	5070	7.071		2.130		2.37	4.825	S.24	10.3
	PULSE	1			1		012	092	400	1.966	120.5	2.75	1	9752	8770	623	535	5.580	0.099		8629	5960	1632	1.535	3046	165.4		1258		1126	5.166	3.436	8.17
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