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Liquid Propulsion Considerations in Projecting Launch Vehicle Failure Probabilities

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LIQUID PROPULSION CONSIDERATIONS IN PROJECTING LAUNCH VEHICLE FAILURE PROBABILITIES

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ABSTRACT

Launch vehicle liquid propulsion failure probabilities are derived from historical data, considering the differing experiences with cryogenic (LOX/LH) and non-cryogenic (LOX/RP or hypergolic) propellant systems. The effect of learning is discussed as is the distribution of failures between engines and the remainder of the propulsion system. Benign failures which lead to engine shutdown without vehicle destruction are segregated from catastrophic propulsion failures. Additionally, propulsion system failure probabilities are projected for launch vehicles with and without sufficient performance margins to achieve mission success when an engine shuts down benignly and with and without vehicle holddown. Projected failure probabilities are compared for current and new launch systems.

FAILURE PROBABILITY ANALYSES

Analyses of U.S. and, where available, foreign space launch vehicles failure histories have provided considerable insight into the causes and types of launch vehicle failures and the learning rates for their failure probabilities. Both failure probabilities and the times that vehicles are non-operational (downtimes) have been associated with propulsion, guidance and "other major subsystems", thus providing insights into how existing and future launch systems can be improved.

Using this data base and projecting improvements in design and technology, permits quantitative projections of future launch vehicle failure probabilities, downtimes and operational capabilities and limitations.

A typical example of failure history for Titan III, shown in Table 1, reveals a pattern of early design failures and continuing "processing" failures. A design failure is, by definition, one which is corrected by a change in design, and typically it does not reoccur, although other problems may be encountered due to the change. Both a design and a process failure may occur on the same launch. Also, a corrective action for a design failure is usually accompanied by a change in the process. Other (than design) failures are random in that they are almost never anticipated as to their nature and time of occurrence. However, examinations of the corrective actions taken after they occur reveal that they are generally due to "escapes" in any of the thousands of manufacturing, assembly and launch preparation processes and activities required for a launch system. The corrective actions generally involve changes in the process including procedures, tests or quality assurance functions (which screen for escapes), non-conformance and defects. Accordingly, they are most appropriately labeled process failures.

Note that, although the Titan III was declared operational after the first few launches, both design and process failures occurred thereafter.

A plot of Titan III failure ratio versus number of launches (excluding Transtage upper stage non-guidance failures), shown in Figure 1, yields a high ratio early in its history due to incipient design failures, and a gradual maturation of the vehicle. This typical learning curve reflects the fact that design failures are generally discovered and corrected early in a flight program.

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*President and Senior Engineer, respectively.
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TABLE 1

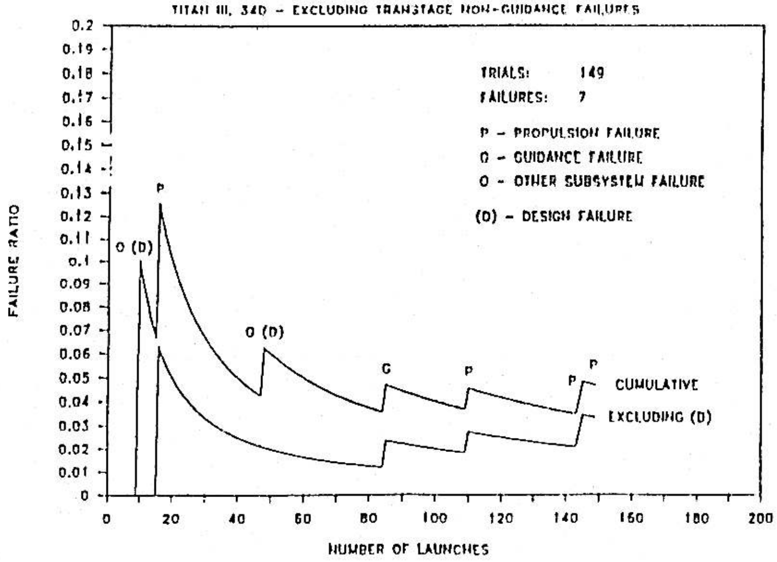
TITAN III
FLIGHT FAILURE HISTORY

PROGRAM PHASE	VEHICLE	DATE	FAILURE	FIX	FAILURE FIX DESIGN	PROCESS
DEVELOPMENT	A-2	09/01/64	T/S PRESSURE SYSTEM FAILURE	QUAD REDUNDANT PRESSURE SYSTEM	X	
	C-4	10/15/64	T/S PROPELLANT FREEZING	ELECTRICAL HEATER ON BI-PROPELLANT VALVE	X	
	C-8	12/21/65	T/S ACS DID NOT SHUT DOWN	INCREASE QUALITY CONTROL LATER - CHANGED TO HYDRAZINE ACS WITH REDUNDANCY	X	X
OPERATIONAL	C-12	08/02/66	PAYLOAD FAIRING FAILURE	METAL PAYLOAD FAIRING	X	X
	B-5	04/25/67	STG II - GROSS CONTAMINATION IN PROPELLANT LINE	INCREASE INSPECTION		X
	C-19	11/06/70	T/S IOS - IMU FAILURE	SPECIAL GYRO TEST LATER - NEW GUIDANCE SYSTEM	X	X
	C-25	05/20/75	T/S IMU FAILURE	RETROFIT WITH X-RAY AND ACOUSTICAL PARTICLE TESTED COMPONENTS PLUS ADDITIONAL SHOCK AND VIBRATION TESTS		X
	C-35	03/25/78	STG II - HYDRAULIC PUMP	PAD X-RAY INSPECTIONS AND ADDITIONAL QUALITY CONTROL ON VENDOR		X
	34D-7	08/28/85	STG I - PROPULSION FAILURE MASSIVE OX LEAK	INCREASE QUALITY CONTROL AND ADDITIONAL TESTING		X
	34D-9	04/08/86	SRM FAILURE - PROBABLY DUE TO CASE/INSULATION DEBOND	IMPROVED PRODUCTION AND HOT PROCEDURES		X

FIGURE 1

FAILURE RATIO HISTORY

TITAN III, 34D - EXCLUDING TRANSTAGE NON-GUIDANCE FAILURES



Deleting design failures results in a process failure ratio curve which shows little evidence of learning and indicates that the vehicle failure probability is driven by process failures associated with the manufacture, assembly, test and launch of the vehicle.

The general distinction between design and processing failures is useful for explaining the notions of incipient and random failures. However, it should be noted that for some systems, design fixes are common throughout the program, perhaps partly as a strategy to upgrade obsolescent subsystems.

Theoretical predictions of launch vehicle failure probabilities utilizing piece part reliability data generally do not include either vehicle design or process failures. As a result, the predictions have been inordinately optimistic, predicting failure probabilities as much as an order of magnitude lower than actually occur.

An essential part of analyzing the U.S. launch vehicle failure history has been to identify the failures by major subsystem - liquid and solid propellant propulsion, guidance and other subsystems. Generally, propulsion system failures exceed those of all other subsystems combined. Accordingly, the description of the analytical approach to projecting failure probabilities should be centered upon propulsion subsystems.

For launch vehicles with liquid engine segment-out capabilities, three major subsystems should be defined: engine segment, stage level and engine segment-out control.

The engine segment includes not only the engine (delivered by the engine contractor) but other subsystems required to enable it to function as an independent propulsion unit.

Analysis of the flight failure data base reveals that about 50 to 70 percent of in-flight propulsion system failures have occurred outside of the engine. Based upon these results, it is clear that engine ground test data cannot be used to predict the total in-flight propulsion system failure ratio because extensive engine ground test programs have generally dealt with only a part of the total propulsion system.

The tank and its associated components operate at the stage level, supplying propellant to the engine segments in a multi-engine vehicle stage. Generally, failures at this level will effect propellant supply to all engine segments, causing failure of the stage propulsion system, and, thus, the launch vehicle.

The engine segment-out control subsystem is designed to shut an engine segment down when it malfunctions in a manner that endangers the launch vehicle and or the achievement of mission success.

To predict the failure probability of a multi-liquid, engine segment-out propulsion system requires knowledge of the values of the following parameters.

Benign Failure Probability (BFP) - The probability that an engine segment will shutdown benignly in flight.

Catastrophic Failure Probability (CFP) - The probability that an engine segment will fail catastrophically in flight, thereby causing the vehicle to fail, even with redundant engines.

Stage (catastrophic) Failure Probability (SFP) - The probability that a failure will occur in a propulsion subsystem at the stage level, thereby causing the vehicle to fail.

Engine Segment-Out Control Subsystem Failure Probability (EFP) - The probability that the engine segment-out control segment will fail, causing mission failure.

The potential for reducing the failure probability with an engine segment-out capability can best be assessed by projecting the values of the above failure probabilities using a flight failure history database. In fact, because process failures have historically dominated the parameter values, theoretical predictions which do not include process failures will be invalid.

The instantaneous engine segment in-flight failure ratios (the reciprocal of the number of launches between failures averaged over N failures) for LOX/LH and non-cryogenic (LOX/RP and hypergolic) engine segments are shown in Figure 2. The curves indicate little or no learning over the flight histories. In fact, there has been a recent increase in the failure ratio for LOX/LH due to failures of newly introduced propulsion systems into the family, the Space Shuttle Main Engine (SSME) and the Arianne upper stage engine. Summarizing the failure history evaluation for LOX/LH propulsion, the in-flight engine segment benign failure ratio, not including these recent transients, is about 0.02 with no catastrophic failures.

Based upon the SSME ground test program and the subsequent limited flight experience, the current engine (only) total and catastrophic failure ratios, shown in Figure 3, are 0.02 and 0.0025 respectively. (There have been no in-flight failures of other subsystems in the engine segment to date).

FIGURE 2

INSTANTANEOUS ENGINE SEGMENT IN-FLIGHT FAILURE RATIO

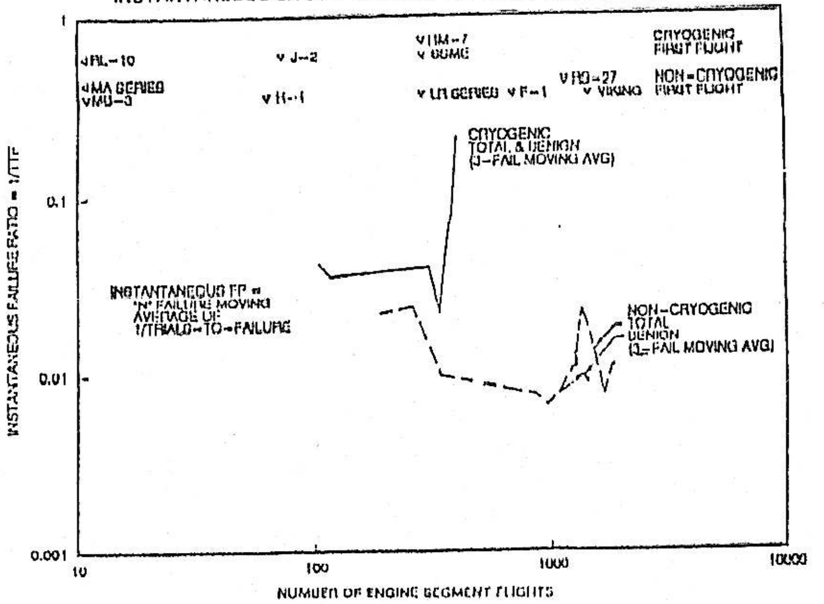
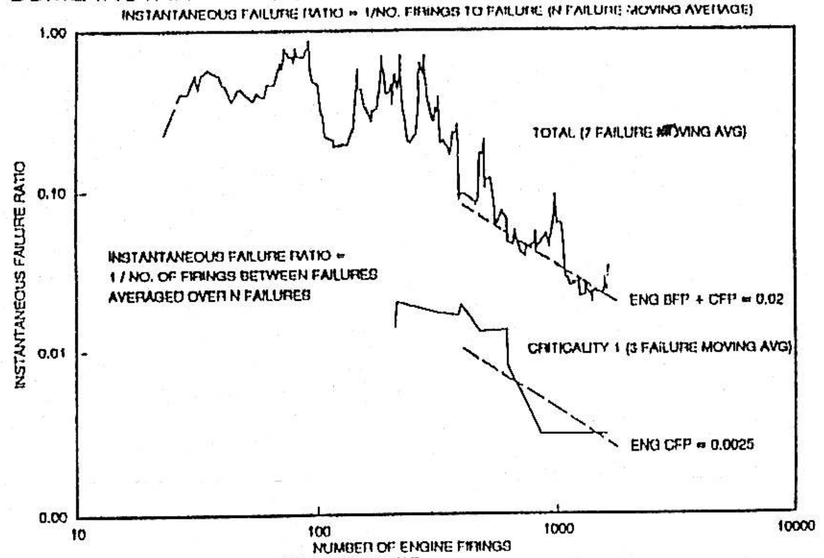


FIGURE 3

SSME INSTANTANEOUS FAILURE RATIO VS. ENGINE FIRINGS

INSTANTANEOUS FAILURE RATIO = 1/NO. FIRINGS TO FAILURE (N FAILURE MOVING AVERAGE)



EXCLUDES FAILURES AT GREATER THAN 104% THROTTLE
AMSTMP2/SSMELOG

The time distribution of in-flight failures can be important when strategies such as on-pad vehicle holddown are used to assure that liquid propulsion systems are fully operable prior to liftoff. For liquid propulsion systems, the time distribution is heavily skewed. It can be seen in Figure 4 that about 50% of all liquid propulsion flight failures started to develop within 5 seconds of engine start; the remaining were distributed roughly proportional to burn time. The distributions are similar for launch vehicles and upper stages. However, early failures were concentrated among Atlas, Centaur, Shuttle, and Titan; Delta and Saturn had no early failures. Therefore the value of holddown is a function of the characteristics of the particular propulsion system. For subsystems other than liquid engines, failures were distributed roughly proportional to flight time.

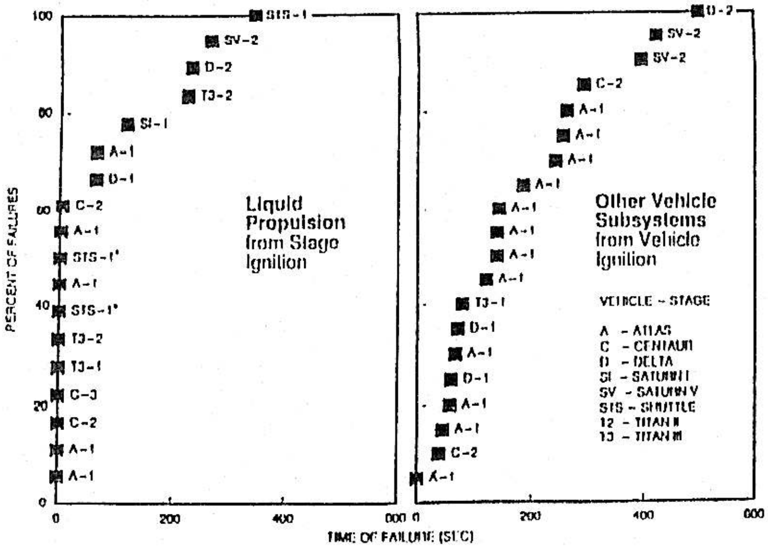
The U.S. liquid propulsion cumulative in-flight for failure ratios are shown in Table 2. Using the data shown here and in Figures 2 and 3, (the reciprocal of the number of launches between failures averaged over N failures) projected mature values - around the 100th vehicle flight - for the Space Transportation Main Engine (STME) are also shown. For the engine segment, the lower benign failure ratio value is based upon the planned conservative design approach for the STME and vehicle holddown at ignition. The projected engine segment catastrophic failure probabilities lie between the historical values for cryogenic and LOX/RP and hypergolic propulsion.

The projections for LOX/RP and hypergolic propulsion are the same as those for LOX/LH except for the engine segment benign failure probability.

Engine segment benign failure probabilities are projected to be lower with the use of a short vehicle holddown after ignition, based on the time of failure distribution (Figure 4) and the experience with Shuttle. Catastrophic failure probability, already a minor contributor, is too uncertain to project a significant holddown benefit.

FIGURE 4

SPACE LAUNCH VEHICLES TIME OF FAILURE HISTORY



* Failure Occurred During Vehicle Holddown

TABLE 2

LIQUID PROPULSION FAILURE RATIO HISTORY

HISTORICAL FAILURE RATIOS	PER STAGE LEVEL	ENGINE SEGMENT BENIGN	ENGINE SEGMENT CATASTROPHIC	ENGINE SEGMENT-OUT CONTROL
CRYOGENIC (LOX/LH)	.021 (4/194)[1]	.020 (9/443)	0 (0/443)	0 (0/61)[2]
LOX/RP AND HYPERGOLIC	.003 (3/1031)	.005 (10/1896)	.002 (3/1896)	0 (0/32)[2]
PROJECTED MATURE FAILURE RATIOS[3]				
STME	.001-.002-.004[3]	.003-.006-.010	.0005-.001-.002	.001-.002-.004
- WITHOUT HOLDDOWN		.005-.009-.015		
LOX/RP AND HYPERGOLIC	.001-.002-.004	.002-.003-.006	.0005-.001-.002	.001-.002-.004
- WITHOUT HOLDDOWN		.003-.005-.010		

[1] NUMBER OF FAILURES/NUMBER OF TRIALS
[2] NUMBER OF TRIALS FOR STAGES WITH ENGINE SEGMENT-OUT CAPABILITY
[3] MATURE VALUES ARE THE EXPECTED VALUES AT ABOUT THE 100TH FLIGHT

At the stage level, the high failure ratio experienced for cryogenic propulsion is driven by multiple failures related to a now deleted Centaur boost pump. Accordingly, the projected stage level failure probability has been chosen to be more consistent with that for LOX/RP and hypergolic propulsion systems.

Maturity is generally an issue for non-engine portions of the propulsion system (and the remainder of the vehicle) because extensive ground tests provide a relatively mature flight engine. (For the purpose of this paper, a "mature" system failure probability is that achieved at about the one hundredth launch; thereafter, failure probability reduction due to learning is minimal.) Differences in failure ratios between the cryogenic and non-cryogenic systems is, in part, due to differences in maturity. The typical non-cryogenic stage has accumulated about two hundred launches versus fifty or less for most cryogenic systems. Thus, design failures weigh heavier for cryogenic systems. Never-the-less, a difference appears to be inherent in their respective failure probabilities at equal maturity.

We have projected similar catastrophic failure probabilities for both classes of propulsion in spite of the uncertainty in the values. The relatively low probability of catastrophic failures implies that without engine segment-out capability, benign failures are dominate, and that with it, the high leverage is in the ability to essentially eliminate vehicle loss due to benign failures. Catastrophic contributions are small in either case for either propellant class.

A review of the U.S. manned flight history reveals two anomalies associated with engine segment-out control subsystems, one each in a Saturn and Shuttle flight. Both are considered anomalies because the vehicles completed their missions. Accordingly, the catastrophic failure probability for that subsystem is projected to be low, in the range of 0.001 to 0.004, nominally 0.002.

The ranges for the projected failure probabilities are necessarily large due to the limitations in the available data.

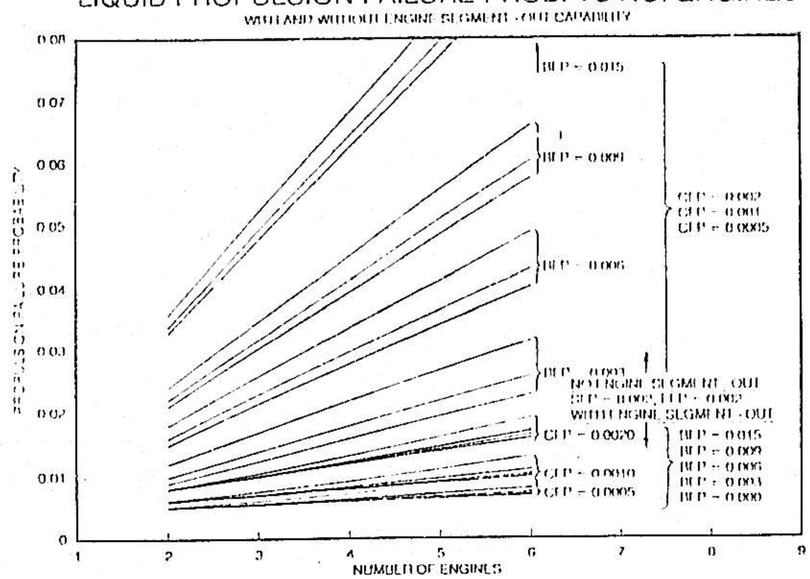
ENGINE SEGMENT-OUT ANALYSES

Historically, liquid rocket boosters have required multiple engines to provide the necessary thrust. Additionally, vehicle performance margins have generally been insufficient to provide for mission success when an engine segment failed benignly. The projected STME values of the four critical failure probabilities - engine segment benign failure probability, BFP = 0.006 (with holddown); engine segment catastrophic failure probability, CFP = 0.001; propulsion stage level catastrophic failure probability, SFP, = 0.002; and engine-out control subsystem failure probability, EFP, = 0.002 - have significant implications for multiple engine launch vehicles of the future.

Figure 5 presents the projected propulsion system failure probability for multiple STME systems with and without an engine segment-out capability.

FIGURE 5

LIQUID PROPULSION FAILURE PROB. VS NO. ENGINES



EOUTTUT/EOUT

Generally, for multiple liquid engine propulsion systems without engine segment-out capability, benign failure probabilities dominate the total contribution of propulsion to vehicle failure probability, and it is evident that the values generally exceed the 0.02 goal for the National Launch System (NLS).

With engine segment-out capability, the benign failure probability contributes very little to the total unless an inordinate number of engines are used. Catastrophic failure probability is the driver, and for most NLS configurations the engine segment benign failure probability can be treated as a minor contributor. Analyses of LOX/RP and hypergolic propulsion systems yield similar results.

MAJOR LESSONS LEARNED

Analyses of flight and to a lesser extent, ground test failure histories have led to significant insights into the characteristics of launch failures. One of the most important lessons learned is that failure causes are rarely predicted by standard reliability calculation methodologies. Indeed, the dominate causes of failure - design weaknesses and processing failures (escapes) - are generally excluded from traditional analyses due to lack of insight and knowledge of the problem. This has led to unrealistically low predictions of launch vehicle failure probabilities.

Other examples of lessons learned are that failures occur frequently in propulsion subsystems other than the engine, making engine-only failure data misleading and that time distribution of failures in flight is heavily skewed for liquid propulsion but not other subsystems. Thus, a launch vehicle holddown strategy to verify nominal propulsion operations could yield substantial reductions in flight failures.

Propulsion failures have been the major cause of launch failures and the preponderance of those have been benign failures, i.e., the engine has failed to provide the required thrust without failing catastrophically. Accordingly, the largest single reduction in failure probabilities for such vehicles could be achieved by designing for engine segment-out capabilities to meet mission requirements.

PROJECTING LAUNCH VEHICLE FAILURE PROBABILITIES

Table 3 presents launch vehicle major subsystems failure ratios (probabilities) based upon analyses of failure histories similar to those described for propulsion. Projected mature failure probabilities for future launch vehicles are generally lower than historical failure ratios because of learning and the assumption that new launch vehicles will benefit from more conservative designs and process controls and technology improvements. A prime example of this is the conservative design planned for the STME currently under development for the NLS program. (Liquid propulsions values are shown assuming holddown.) Lower failure probabilities are also projected for solid propulsion assuming improved processing and non-destructive testing techniques. A significant reduction is also projected for guidance assuming the introduction of redundancy, including voting.

TABLE 3

NLS PROJECTED SUBSYSTEM PER UNIT FAILURE PROBABILITIES

SUBSYSTEM	HISTORICAL FLIGHT FAILURE RATIOS[1]	IMPROVEMENTS	PROJECTED MATURE[2] FAILURE PROBABILITIES LOW	NOM	HIGH
SOLID PROPULSION					
MONOLITHIC	.001	MARGINS/ PROCESS CONTROL	.0005	.001	.0015
SEGMENTED/TVC	.007		.003	.005	.007
LIQUID PROPULSION					
ENGINE SEGMENT BENIGN (BFP)		MARGINS/ HOLDDOWN			
- CRYOGENIC	.020		.003	.006	.010
- LOX/RP OR HYPERGOLIC	.008		.002	.003	.007
ENGINE SEGMENT CATASTROPHIC (CFP)	0-.002		.0005	.001	.002
STAGE LEVEL (SFP)	.002-.021		.001	.002	.004
ENGINE SEGMENT-OUT CONTROL SUBSYSTEM	0[3]		.001	.002	.004
NON-PROPULSIVE					
GUIDANCE, BENIGN	.016	ADVANCED TECHNOLOGY REDUNDANCY	.003	.005	.006
GUIDANCE, CATASTROPHIC	.002		.0003	.0005	.0008
OTHER, VOTING LOGIC	0		.0003	.0005	.0008
OTHER, PER VEHICLE	.012		.002	.003	.005
OTHER, PER STAGE	.006		.001	.002	.004

[1] INCLUDES DESIGN FAILURES
[2] AT 100TH LAUNCH
[3] .011 IF INFLIGHT ANOMALIES ARE CONSIDERED

These projections - nominal values and their associated low and high values - are treated as per unit failure probabilities in a mature NLS configuration. The ranges from the estimated low to the high values vary from a factor of two to four for the various subsystems.

Using the projected subsystem failure probabilities from Table 3, the currently projected mission failure probabilities for the existing fleet are shown in Figure 6 compared to the National Launch System (NLS) baseline vehicles with and without engine segment-out capabilities. The current DoD baseline is an all liquid engine stage and a half (4/2 1.5) with 6 STMEs, 4 of which are staged early in the trajectory. An alternative to the DoD baseline vehicle could be a stage and a half with 5 STMEs (4/1 1.5) with no engine segment-out capability. The NASA baseline uses Advanced Solid Rocket Boosters (ASRB) and a cryogenic core stage propelled by either 4 or 3 STMEs, (HLLV-4 or HLLV-3).

Several important points can be made about the projected failure probabilities.

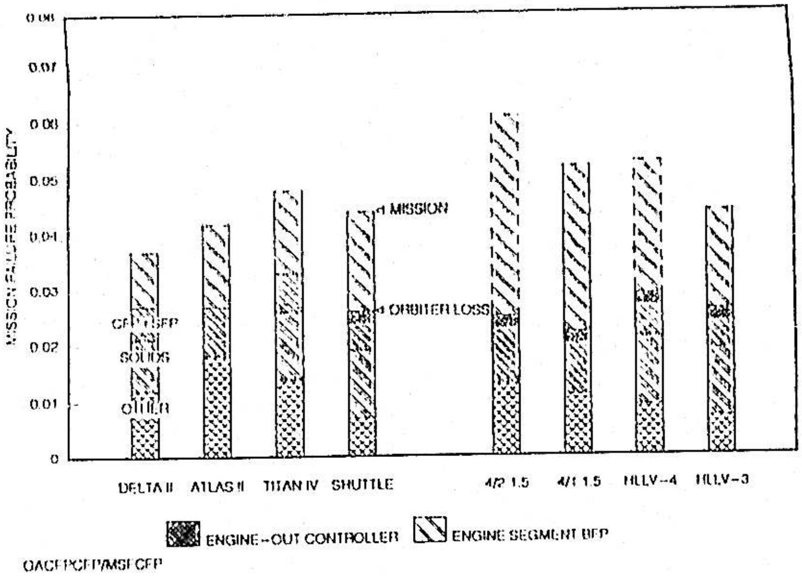
One half or more of the current vehicle mission failure probabilities are due to propulsion, with more than half being due to benign engine segment failure probabilities in the cases of Atlas II and Shuttle. (When a benign SSME segment failure occurs, the Shuttle goes into an abort mode and generally the Orbiter does not reach its mission orbit.)

- The 1.5 stage and HLLV vehicles without engine segment-out capabilities are projected to have failure probabilities comparable to those of the current fleet. With engine segment-out capabilities, their failure probabilities are projected to be about one half of than those for the current fleet.

- The NASA HLLV baseline vehicle without engine segment-out capabilities is projected to have a mission failure probability about equal that of the Shuttle, but would have a higher probability of payload loss because it would not have an abort capability.

FIGURE 6

FLEET MATURE MISSION FAILURE PROBABILITIES



incorporate into next generation launch vehicles utilizing multiple liquid engine propulsion are vehicle holddown and engine segment-out capabilities to achieve mission success. These features can be expected to reduce the vehicle failure probabilities by a factor of about 2, the reduction depending upon the number of liquid engines. Accordingly, launch vehicles should be designed to provide the flexibility to operate with and without engine segment-out capabilities, with different criteria depending upon payload value and whether the payload is manned or unmanned.

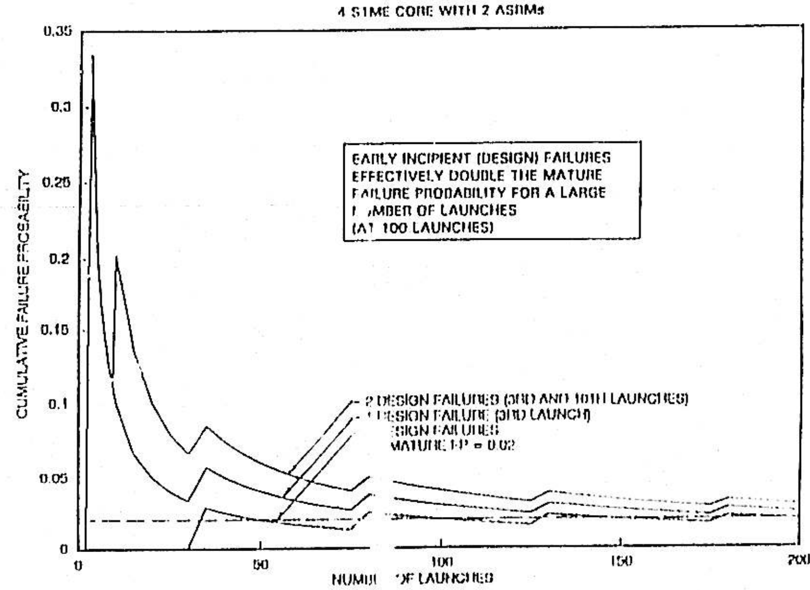
The contribution of the engine segment-out control subsystem failure probability to the vehicle failure probability is projected to be small as compared to the probabilities of engine segment benign failures.

The prior estimates were for mature vehicles. Any program plans should anticipate potential design failures. The impact of design failures on cumulative failure probability is dramatic in the early launches, as shown in Figure 7, which assumes a 0.02 mature failure probability and 1 or 2 early design failures. (Based on historical trends, 2 could be expected.) With the occurrence of early design failures, the cumulative failure probability approaches the mature value very gradually.

FIGURE 7

CUMULATIVE FAILURE PROBABILITY WITH DESIGN FAILURES

4 STME CORE WITH 2 ASRMs



SUMMARY

Analyses of launch vehicle failures reveal that about one half or more have been due to propulsion failures which are largely liquid engine segment benign failures. Accordingly, the most important features to

FIGURE 1

FAILURE RATIO HISTORY

TITAN III, 34D – EXCLUDING TRANSTAGE NON-GUIDANCE FAILURES

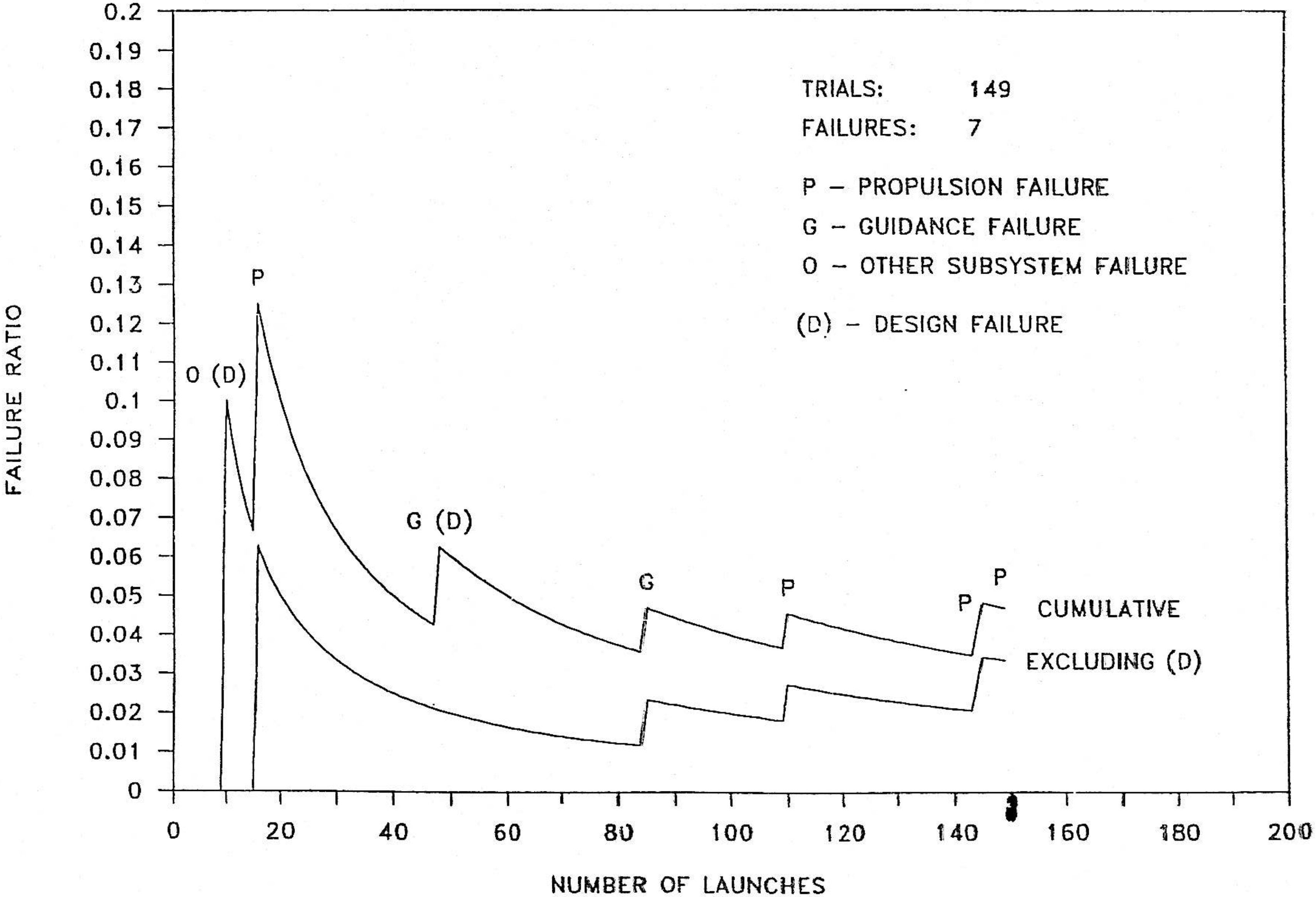
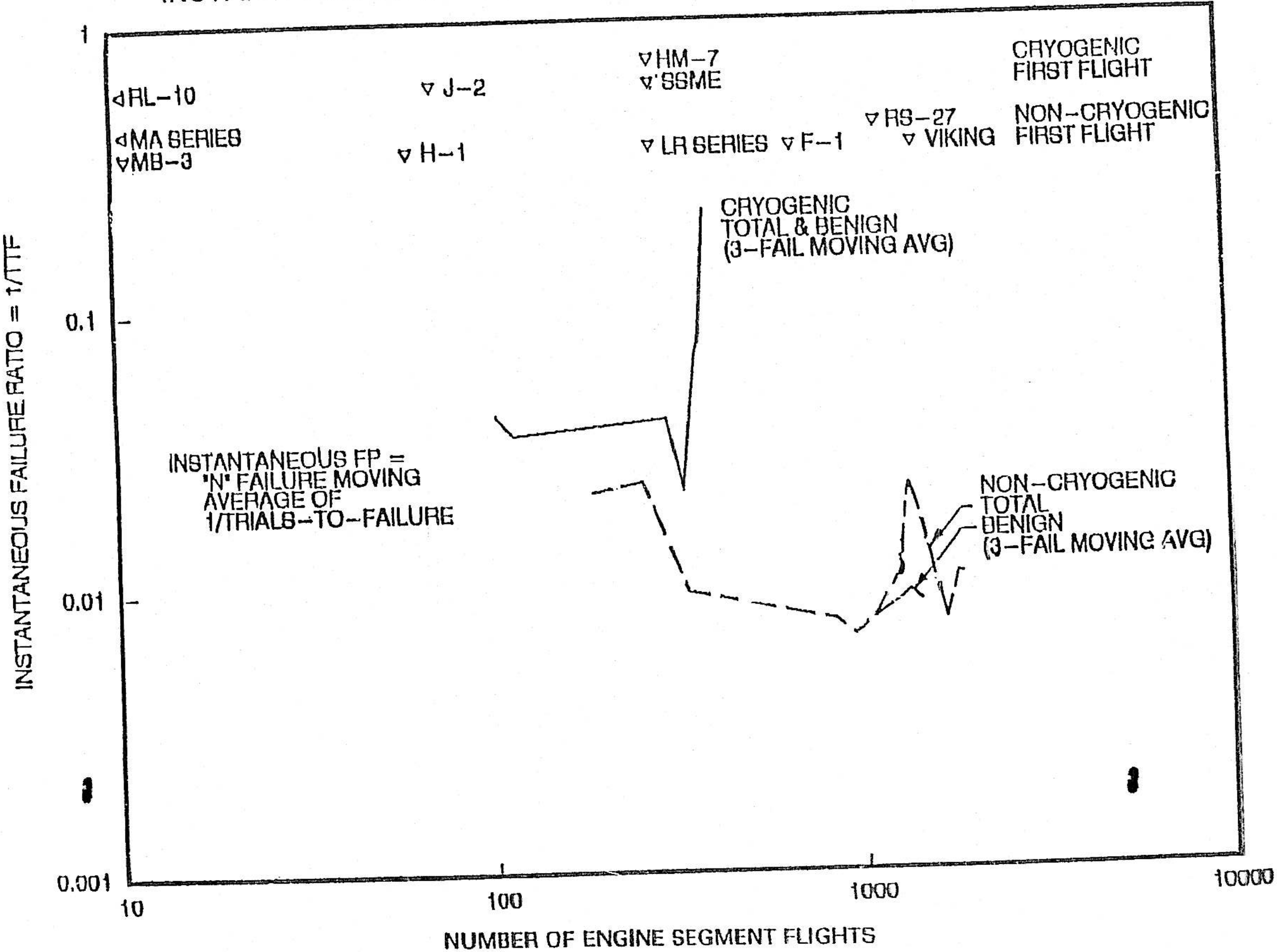


FIGURE 2

INSTANTANEOUS ENGINE SEGMENT IN-FLIGHT FAILURE RATIO



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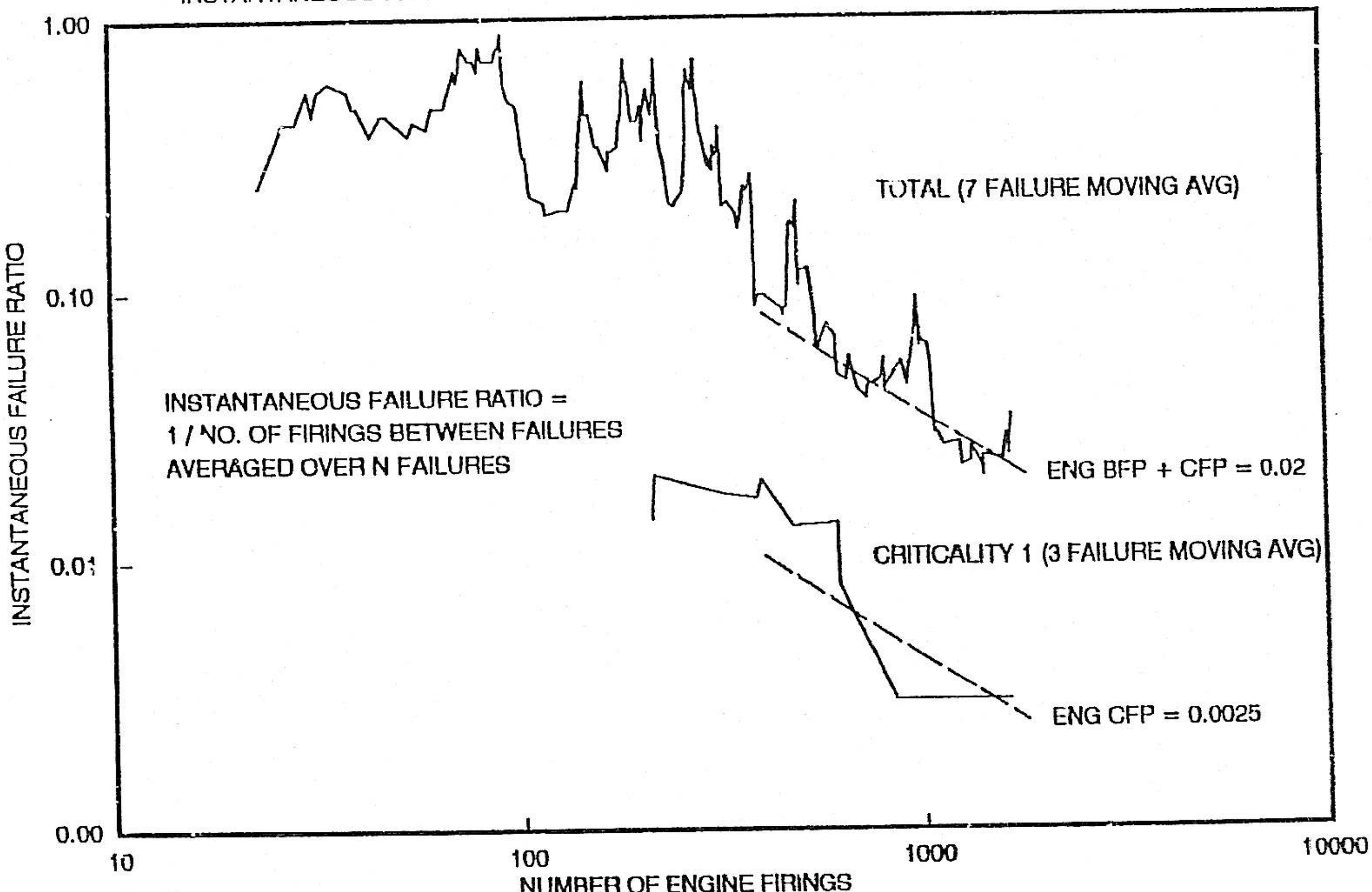
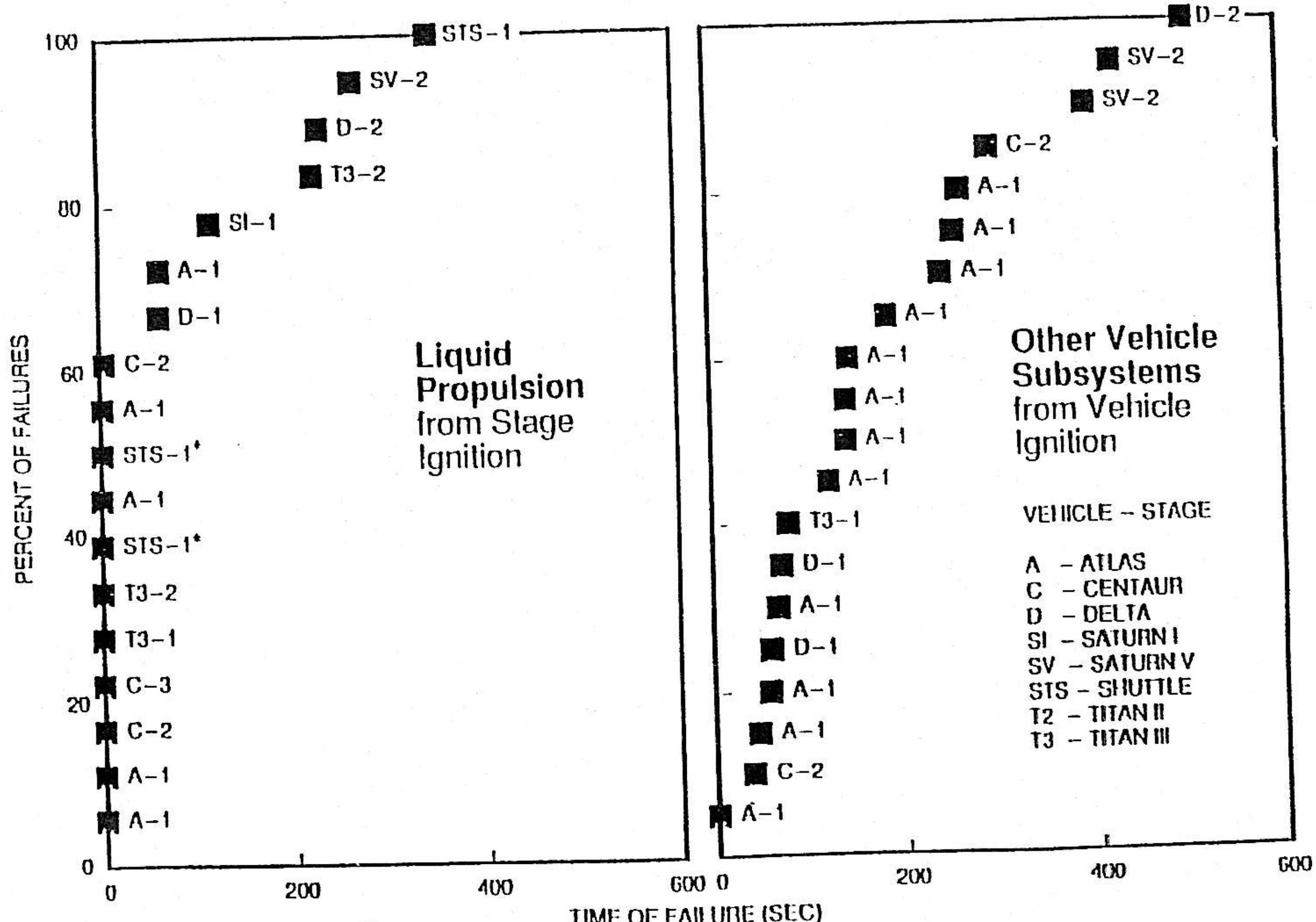


EXCLUDES FAILURES AT GREATER THAN 104% THROTTLE
AMSTMP2/SSMELOG

FIGURE 4

SPACE LAUNCH VEHICLES TIME OF FAILURE HISTORY

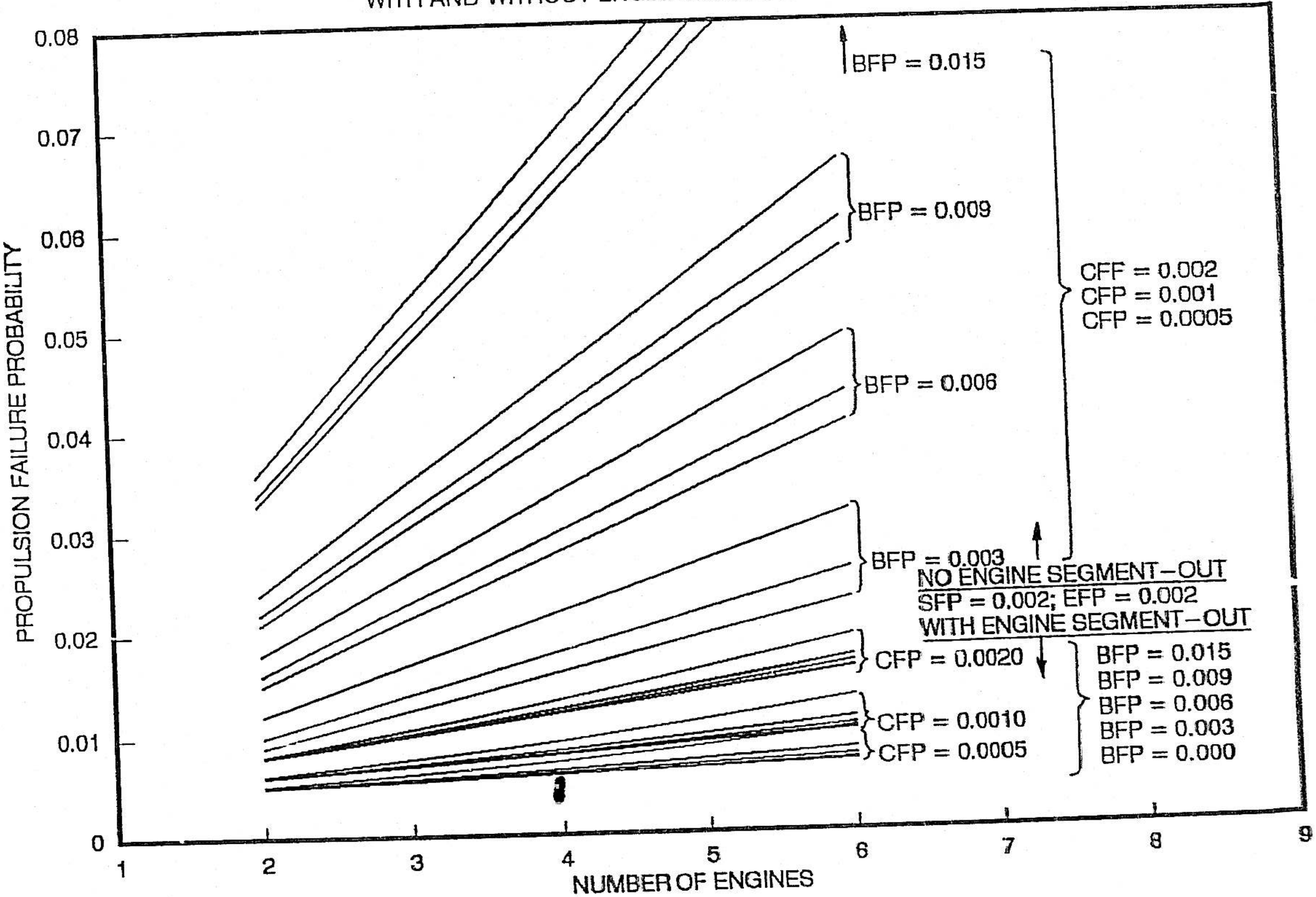


* Failure Occurred During Vehicle Holddown

FIGURE 5

LIQUID PROPULSION FAILURE PROB. VS NO. ENGINES

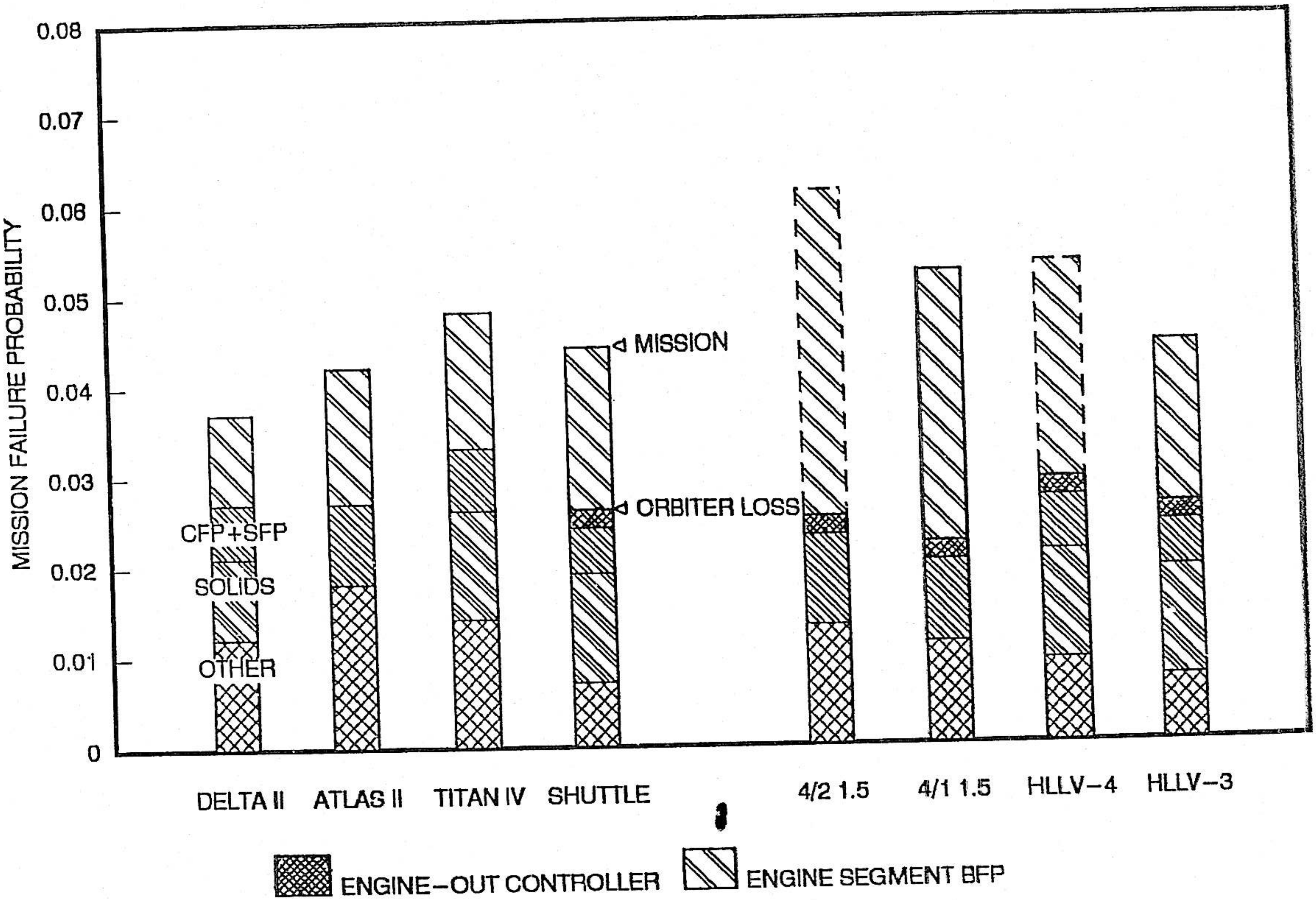
WITH AND WITHOUT ENGINE SEGMENT–OUT CAPABILITY



EOUTTUT/EOUT

FIGURE 6

FLEET MATURE MISSION FAILURE PROBABILITIES

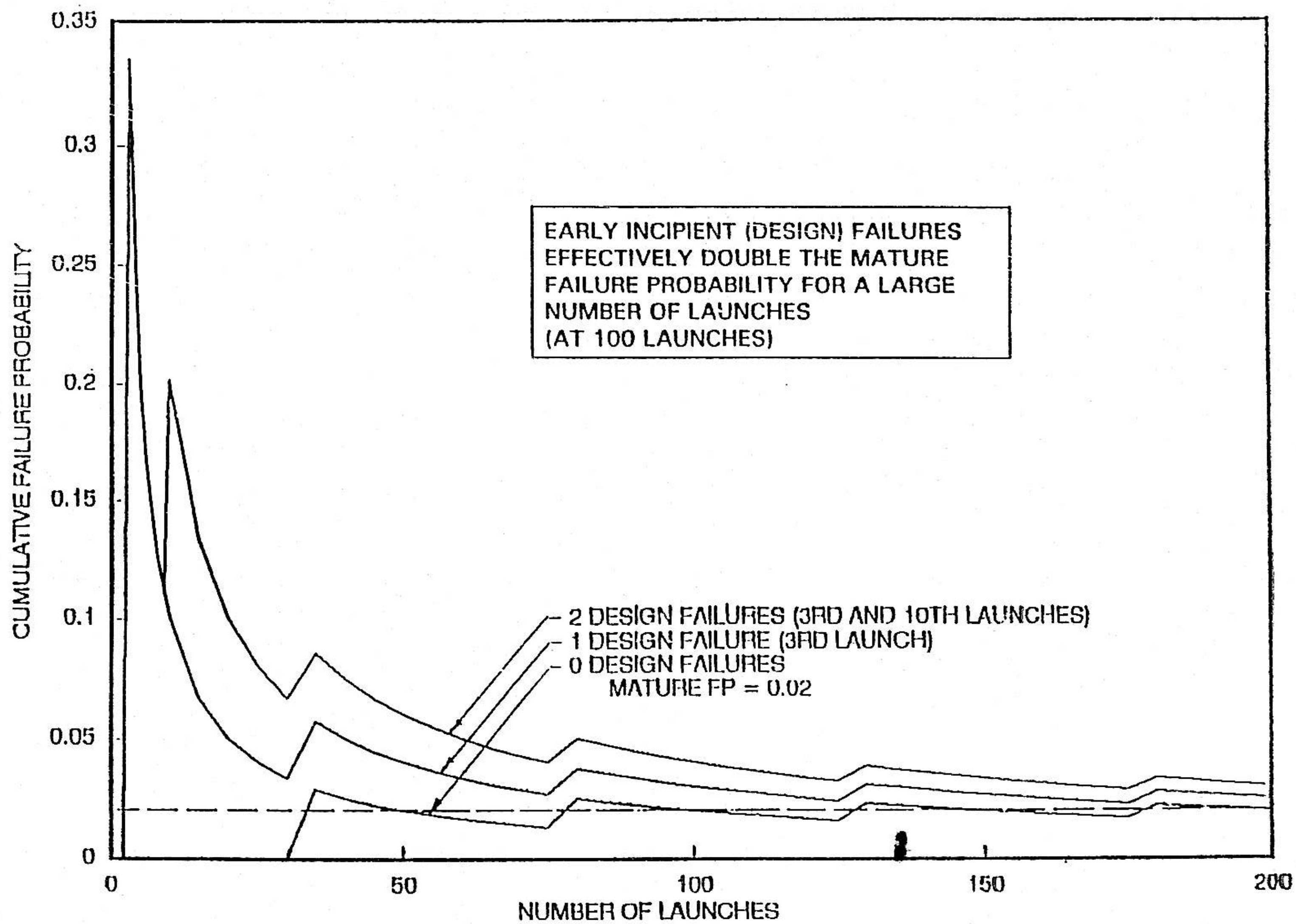


GACFPCFP/MSFCFP

FIGURE 7

CUMULATIVE FAILURE PROBABILITY WITH DESIGN FAILURES

4 STME CORE WITH 2 ASRMs



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	C-4	10/15/64	T/S PROPELLANT FREEZING	ELECTRICAL HEATER ON BI-PROPELLANT VALVE	X	
	C-8	12/21/65	T/S ACS DID NOT SHUT DOWN	INCREASE QUALITY CONTROL LATER - CHANGED TO HYDRAZINE ACS WITH REDUNDANCY	X	X
OPERATIONAL	C-12	08/02/66	PAYLOAD FAIRING FAILURE	METAL PAYLOAD FAIRING	X	X
	B-5	04/25/67	STG II - GROSS CONTAMINATION IN PROPELLANT LINE	INCREASE INSPECTION		X
	C-19	11/06/70	T/S IGS - IMU FAILURE	SPECIAL GYRO TEST LATER - NEW GUIDANCE SYSTEM	X	X
	C-25	05/20/75	T/S IMU FAILURE	RETROFIT WITH X-RAY AND ACOUSTICAL PARTICLE TESTED COMPONENTS PLUS ADDITIONAL SHOCK AND VIBRATION TESTS		X
	C-35	03/25/78	STG II - HYDRAULIC PUMP	PAD X-RAY INSPECTIONS AND ADDITIONAL QUALITY CONTROL ON VENDOR		X
	34D-7	08/28/85	STG I - PROPULSION FAILURE MASSIVE OX LEAK	INCREASE QUALITY CONTROL AND ADDITIONAL TESTING		X
	34D-9	04/08/86	SRM FAILURE - PROBABLY DUE TO CASE/INSULATION DEBOND	IMPROVED PRODUCTION AND NDT PROCEDURES		X

TABLE 2

LIQUID PROPULSION FAILURE RATIO HISTORY

HISTORICAL FAILURE RATIOS	PER STAGE LEVEL	ENGINE SEGMENT BENIGN	ENGINE SEGMENT CATASTROPHIC	ENGINE SEGMENT-OUT CONTROL
CRYOGENIC (LOX/LH)	.021 (4/194)[1]	.020 (9/443)	0 (0/443)	0 (0/61)[2]
LOX/RP AND HYPERGOLIC	.003 (3/1031)	.005 (10/1896)	.002 (3/1896)	0 (0/32)[2]
PROJECTED MATURE FAILURE RATIOS[3]				
STME - WITHOUT HOLDDOWN	.001-.002-004[3]	.003-.006-.010 .005-.009-.015	.0005-.001-.002	.001-.002-.004
LOX/RP AND HYPERGOLIC - WITHOUT HOLDDOWN	.001-.002-004	.002-.003-006 .003-.005-.010	.0005-.001-.002	.001-.002-.004

1) NUMBER OF FAILURES/NUMBER OF TRIALS
2) NUMBER OF TRIALS FOR STAGES WITH ENGINE SEGMENT-OUT CAPABILITY
3) MATURE VALUES ARE THE EXPECTED VALUES AT ABOUT THE 100TH FLIGHT

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SUBSYSTEM	HISTORICAL FLIGHT FAILURE RATIOS[1]	IMPROVEMENTS	PROJECTED MATURE[2] FAILURE PROBABILITIES LOW - NOM - HIGH
SOLID PROPULSION			
MONOLITHIC	.001	MARGINS/ PROCESS CONTROL	.0005 - .001 - .0015
SEGMENTED/TVC	.007		.003 - .005 - .007
LIQUID PROPULSION			
ENGINE SEGMENT BENIGN (BFP)		MARGINS/ HOLDDOWN	
- CRYOGENIC	.020		.003 - .006 - .010
- LOX/RP OR HYPERGOLIC	.006		.002 - .003 - .007
ENGINE SEGMENT CATASTROPHIC (CFP)	0-.002		.0005 - .001 - .002
STAGE LEVEL (SFP)	.002-.021		.001 - .002 - .004
ENGINE SEGMENT-OUT CONTROL SUBSYSTEM	0[3]		.001 - .002 - .004
NON-PROPULSIVE			
GUIDANCE, BENIGN	.016	ADVANCED TECHNOLOGY/ REDUNDANCY	.003 - .005 - .006
GUIDANCE, CATASTROPHIC	.002		.0003 - .0005 - .0008
OTHER, VOTING LOGIC	0		.0003 - .0005 - .0008
OTHER, PER VEHICLE	.012		.002 - .003 - .005
OTHER, PER STAGE	.006		.001 - .002 - .004

1) INCLUDES DESIGN FAILURES
2) AT 100TH LAUNCH
3) .011 IF INFLIGHT ANOMALIES ARE CONSIDERED