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~~Copy 2 of 9~~
32 Pages ~~of attch.~~

To: B. P. Leonard
W. F. Sampson
W. C. Williams

cc: Below

16 May 1966

L. M. Weeks

Subject: Reliability Growth and Cost Effectiveness Comparison of Manned and Unmanned MOL Systems

cc: E. Barlow/A. Donovan/W. Leverton
S. Tenant/H. Bernstein
F. P. Klein/A. Norem/W. Targoff
S. Strong/L. Lidstrom/G. D. McGhee
File - C. Rasch (2) (one copy to be read by: H. W. Nordyke
W. Pittman
B. Moss
J. Henry)

Subject: RELIABILITY GROWTH AND COST EFFECTIVENESS COMPARISON OF MANNED AND UNMANNED MOL SYSTEMS

1. There has been much discussion regarding reliability growth and cost effectiveness comparisons of manned and unmanned systems during the past few years at Aerospace. Since a major briefing and position paper is to go to the Secretary of Defense in early June, I feel it desirable to go formally on record with the enclosed data. The first pages will attempt to summarize as concisely as possible the data which is enclosed.

2. We are placing in the MOL program a very great emphasis on the simplest and most reliable method of obtaining [redacted] pictures for the longest possible duration. This emphasis is delinated in Enclosure A. We believe that this design configuration emphasis will result in a much higher reliability for the manned version than can possibly be hoped for in the unmanned case.

3. Enclosure B shows the reliability growth of Program X. This shows an un-manned device starting at 20% reliability and growing to 45% reliability. MOL has about 6 times the duration and 6 times the complexity as measured by a number of AEG's. Assuming that we have 100% redundancy in the unmanned mode we have a factor of at least 3 in complexity. Therefore, a lower bound for the reliability growth of our unmanned MOL system would be 45% divided by 18, or about 3%. It seems to the writer that a very optimistic upper bound for MOL in an unmanned mode is Program X, as flown. We note with interest that had Program X been manned the first 4 flights would have been successful. We note with interest that the present MOL program only has 5 flights. We note with interest that an unmanned MOL program with no manned flights to proceed it would have about 25% times 5 flights, or an expected 1 - 1/4 successes. At a cost of $85M per flight in the unmanned mode we note that the 5 flights would cost $425M with only an expected value of 1 - 1/4 successes. Should a lower bound view (3%) be taken of the reliability growth we would spend $425M and not even get one success.

4. The Agena history as flown, and a reconstructed manned vehicle, is shown in Enclosure C. Agena has about 6,000 active element groups.

5. The Mercury reliability growth as flown, and in a reconstructed unmanned case, is shown in Enclosure D. This clearly shows that Mercury in its 4 flights was a complete success in the manned version, whereas had it been unmanned only 25% success would have been attained.

6. The NASA Gemini is shown in Enclosure E. This shows a 90% success on 6 flights in the manned mode whereas the reconstructed unmanned case for that program would have been 25%.

7. Enclosure F shows plots of the reliability growth of Agena, Mercury and Gemini.

8. Enclosure G shows the actual failures per day of various programs and is a useful tool in attempting to estimate the reliability growth that can be expected out of the manned program to improve the reliability growth of the unmanned system. The fundamental message is that Gemini had about 1 anomaly (which is a failure that required the use of redundancy or backup or degradation in order to finish the mission with success). Due to the larger number of AEG's in the MOL, as high as 3 anomalies/day may occur early in the program. Douglas has made some mature estimates which are as low as 1/4 of an anomaly per day at maturity. It is our belief that the case is of the order of one anomaly per day during the development program.

9. Enclosure H shows some mature reliability estimates for the MOL manned/automatic and automatic modes. It should be clearly understood that calculations of this nature are mature reliability and do not address the question of reliability growth.

10. Enclosure B through H are through the courtesty of Phil Klein.

11. Bob Rogers has examined all manned spacecraft of the world and this shows that Vostok, Voskod, Mercury and Gemini in the manned modes are for all practical purposes 100% reliable.

12. Enclosure J shows these same manned spacecraft and their unmanned precursors as best we can examine it, and basically shows that the Soviet's

5 unmanned versions of Vostok had an average reliability of about 50%, whereas the unmanned orbital versions of Mercury were about 80%.

13. Enclosures K and L show the Mercury, Gemini, Vostok and Voskod, both manned and unmanned success ratio plotted versus calendar year. Much more backup data is available upon request.

14. Enclosures J through R are through the courtesy of Bob Rogers.

15. Enclosure M (pages 1 and 2) shows the reliability growth of simple unmanned spacecraft systems. These spacecraft have less then 2, 000 AEG's and have simple or non-existent stabilization systems (i. e., some are spin stabilized). These 45 spacecraft flights have a cumulative average reliability of 72%. The conclusion here is that simple spacecraft with spin stabilization can give one to two year life. (Examples are VELA, TIROS, SYNCOM, TELSTAR and RELAY.)

16. Enclosure N shows the reliability growth of complex unmanned spacecraft. All of these complex spacecraft have a number of AEG from 2, 000 for OSO to 17, 000 for OAO. All of these spacecraft have "complex" attitude control systems. It will be noted that at the 25th launch a reliability of . 8 was achieved. It should also be noted that these 4 successes were the 4th Mariner, the second OSO and the 8th and 9th Rangers. The cumulative average is . 34.

17. Enclosure P shows the reliability growth of Discoverer which shows 12 failures before its first success.

18. Enclosure Q shows the reliability growth of Ranger. Ranger had six failures before its first success.

19. Complex spacecraft with active stabilization systems and/or complex orbit injection requirements have had a 10% to 50% success probability when flown unmanned for 1 week to 7 months. Examples: RANGER, MARINER, LUNA, MIDAS, AGENA-DISCOVERER.

20. I understand that 698BJ had 5 failures in 5 attempts before cancellation. Enclosure R shows the fraction of planned objectives achieved versus a number of active element groups. It is our view that simple unmanned spacecraft can

be reliable. Complex unmanned spacecraft have great difficulty in achieving even modest reliability. The MOL program is a modest extrapolation of Gemini duration and complexity. MOL unmanned is a much greater extrapolation of present unmanned capability. All manned U. S. spacecraft have accomplished planned stay on-orbit except Gemini 8, which still performed 2 out of 3 major objectives and returned its crew safely. Manual control and/or intervention by crew was required and effective on Mercury MA-6, MA-7 and MA-9; and Gemini GT-3, GT-5, GT-7 and GT-8.

21. Enclosure S shows that there is a synergetic effect of redundancy and man in the loop. This analysis of X-15 shows that redundancy only is not a major contributor to improved reliability. This is undoubtedly due to the pilots ability to diagnose and reliably switch to the redundant systems when required. One of the current bugaboos of redundancy is the absolute necessity of higher reliability switches and sensors to tell when and how to switch. The magnitude of the switch reliability in unmanned systems (or in any system) must be an order of magnitude better than the reliability of the systems or the redundancy may not pay off at all (i. e., have redundancy and be worse off).

22. Enclosure T shows the MOL reliability growth versus flights for both the manned and the unmanned program using Program X as a basis (optimistic).

23. Enclosure U shows the reliability growth versus flights for the MOL in a manned and an unmanned mode using Agena as a basis (optimistic).

24. The present cost of the MOL program for option six is $1, 714M. If the automatic part of the program were to be eliminated we would save $254M resulting in a $1, 460M program for a manned only MOL program. We have estimated a completely unmanned MOL program by looking at each subsystem and by adding two additional flights making a total of 7 for an unmanned program, and this cost is $1, 506M. The reliability cost which has been discussed leads us to believe that it is necessary to have a 7-shot unmanned development program to have an adequate reliability to proceed with an operational program. We have estimated the cost of each manned MOL at $102. 1M per flight. I have estimated

the manned/automatic at $106.7M per flight. We have estimated an unmanned version of M/AM to cost $84.6M per flight. (Courtesy of John Wilson)

25. Enclosure V shows the total program costs for 5 years as a function for two different bases - the Agena base and the Program X base. These data show that the reliability growth is a key factor in the comparison of manned and unmanned systems. On the Program X basis the manned and unmanned are a standoff. To obtain this high a reliability requires and extrapolation of 18:1 for duration and complexity - an optimistic assumption on the reliability growth of the unmanned system. The Agena shows that using the manned/AM to develop the unmanned can be cost effective in later years providing approximately 8 manned flights are used to develop the unmanned version. Using Gemini as a base we would find manned at 90% reliability and unmanned at 25%. Therefore, the manned system is -

$$\left[\left(\frac{84.5}{102.1}\right)\left(\frac{.90}{.25}\right) = 2.33\right]$$

133% more cost effective than the unmanned system.

26. Details on the cost comparison of MAM only and unmanned are available from John Wilson upon request.

ENCLOSURE A

A COMPARISON OF THE MANNED AND UNMANNED VERSIONS OF MOL

1. The manned MOL system does not require the use of the V/r sensor. This instrument is relatively undeveloped and quite complex, yet it is a mandatory instrument for the unmanned system and must be developed on time and highly reliably, whereas it is totally unnecessary for the manned system.

2. The unmanned MOL system requires the use of star trackers, which is another major development that is unnecessary in the manned system.

3. It is highly desirable (if not mandatory) for the unmanned system to have an across-the-format IMC (Image Motion Comparison). Eastman Kodak is alleged to believe that this will complicate their 9-1/2" camera. It is not certain at this juncture that failure of across-the-format IMC can, for certain, avoid failure in the manned case of the 9-1/2" camera (i.e., fail-safe). Therefore, the across-the-format IMC for the manned system should probably be avoided.

4. In the manned case should the 9-1/2" camera fail, it is our opinion that enough film should be taken along for the 5" camera to photograph a large percentage of the high priority targets. So in the manned case, not only can we have a simpler 9-1/2" camera, but can get complete backup from a third camera system, if you will, to "guarantee" camera operation on orbit.

5. The unmanned system is presently configured to operate with the low g accelerometer. This accelerometer is a development that only one company elected to bid to GE. This indicates that low g accelerometers are not present state-of-the-art. For the manned system the low g accelerometer (and attendant computer program) is not required.

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6. It is required that a large amount of data be reliably transmitted through the spacecraft to operate successfully in the unmanned mode. In the manned mode the only mandatory items to get to the spacecraft are time to go and roll angle of the target. In the MOL system we have a dual SGLS system.

This data is supposed to go directly to the computer in the normal mode. In the manned system the communication system has a "third" alternate mode using the teleprinters. In the manned system we have a "fourth" and "fifth" alternate mode to get this key targeting data via voice to the crew. Since there will only be 20 or so targets per orbit, it is quite simple by secure voice to send up these few numbers that are crucial to the success of getting pictures. By some standards this could be considered 500% redundancy.

7. The MOL system has dual computers. In the unmanned case additional equipment is needed to sense which computer is operating currently and switch on the operable computer. In the manned case it is quite simple for the astronaut to image some practice targets before the run to decide which computer is operating correctly.

8. The interface between the computer and the tracking mirror is accomplished by mission module data adapter units. These are dual. Target centering is accomplished in the manned system by dual (redundant) acquisition and tracking scopes. In the unmanned case there is no certainty that the target will be in the field-of-view. It is, of course, hoped that the unmanned navigation system, with its attendant complexity, will get the target in the 1° field-of-view.

9. The rate gyros on the pitch and roll axes of the tracking mirror are redundant. We would expect the astronaut to try out and select the operable set of rate gyros on a practice target prior to a run over the Soviet Union (or other target areas).

10. I am told (Bob Gaylord) there are plans for redundant pitch and roll torquers for the tracking mirror. We would again expect the crew to make a trial run to select the better set of torquers to drive the tracking mirror by operating on a practice target.

11. The attitude control system is composed of about 5 or 6 modes in the manual case. A number of the NASA Mercury and Gemini flights have shown that by manual operation the spacecraft can be held to about 1° in angle and rates that are about half to 1/3 that accomplished in the autopilot mode. The astronauts should be expected to try out the coarse mode, the fine mode, the orbit plane mode, the ground track mode, the ion sensor mode; and, if all of these fail, then it is our plan that the crew would directly control the thrusters and align the

spacecraft to the ground track and the horizon and trim to low rates and then permit the tracking mirror to do its job. This means not only many modes, which back each other up, but in the final analysis there is no electronics between the stick and the thrusters; therefore, we expect a very high reliability.

12. The translation propulsion system is "400%" redundant from a thruster point of view. It is expected that the crew will know whether 1, 2, 3 or 4 engines are firing by observing the accelerometer display. They (or he) will also be able to tell from yaw or pitch whether there is an asymmetric longitudinal thrust. Once deciding how many engines are firing and observing the integrating accelerometer, it is easy for the crew to decide the required burning time and perform a manual shutoff target to get very accurate ΔV for orbit adjustment. So in effect, all that is needed to have orbit adjust propulsion is manual attitude control plus a clock. We will provide redundant clocks. The limiting case should be the navigators wrist watch with a sweep second hand.

13. The attitude propulsion tankage system is composed of 4 pairs of oxidizers and fuel which can be considered 400% redundant. Should it be found that three of the pairs have failed, it is necessary for the crew to use 3 or 4 hundred pounds of propellant to raise the perigee and then use the remaining fuel in the pair of tanks for attitude control and, of course, the crew must husband the fuel. The attitude thrusters can permit any two engines out and still control pitch, yaw, and roll. In the Gemini case except for GT-8, two thrusters failed closed on every manned flight and, needless to say, these manned flights were 100% successful. The GT-8 flight, where a thruster failed open was a dramatic example of success in manned missions, whereas unmanned missions would have been total catastrophe.

14. The MOL system incorporates three fuel cells, any one of which will permit continuance of the mission. Full and complete operation of all facets of the mission can be done with only two of the cells operating. Should two fuel cells fail, we are examining to what extent we can conserve power and attempt to get a limited number of [redacted] images.

15. The case of the stuck mirror is being examined to see what degraded modes may be possible under these conditions.

16. We are quite sure that much more work needs to be done on each and every subsystem and sub-subsystem to improve the operability of the manned (and unmanned) MOL in degraded, degraded, degraded modes.

CONCLUSION

A. We shall attempt to quantify the previously mentioned items.

B. It is quite clear that for this MOL Dorian mission that the manned system can (if we do our job right) be made in the same reliability class as Gemini-A was with its 26,000 active element groups for 14 days, although MOL has 42,000 active element groups and a 30-day mission.

C. Although we have in the unmanned MOL a great amount of redundancy, it should be clearly understood that a number of complex equipments such as the Star Tracker, V/r sensor, and the digital communication link are a mandatory part of the unmanned system and are not needed at all for the manned system.

D. The concept for the manned MOL shall be "elegance in simplicity".

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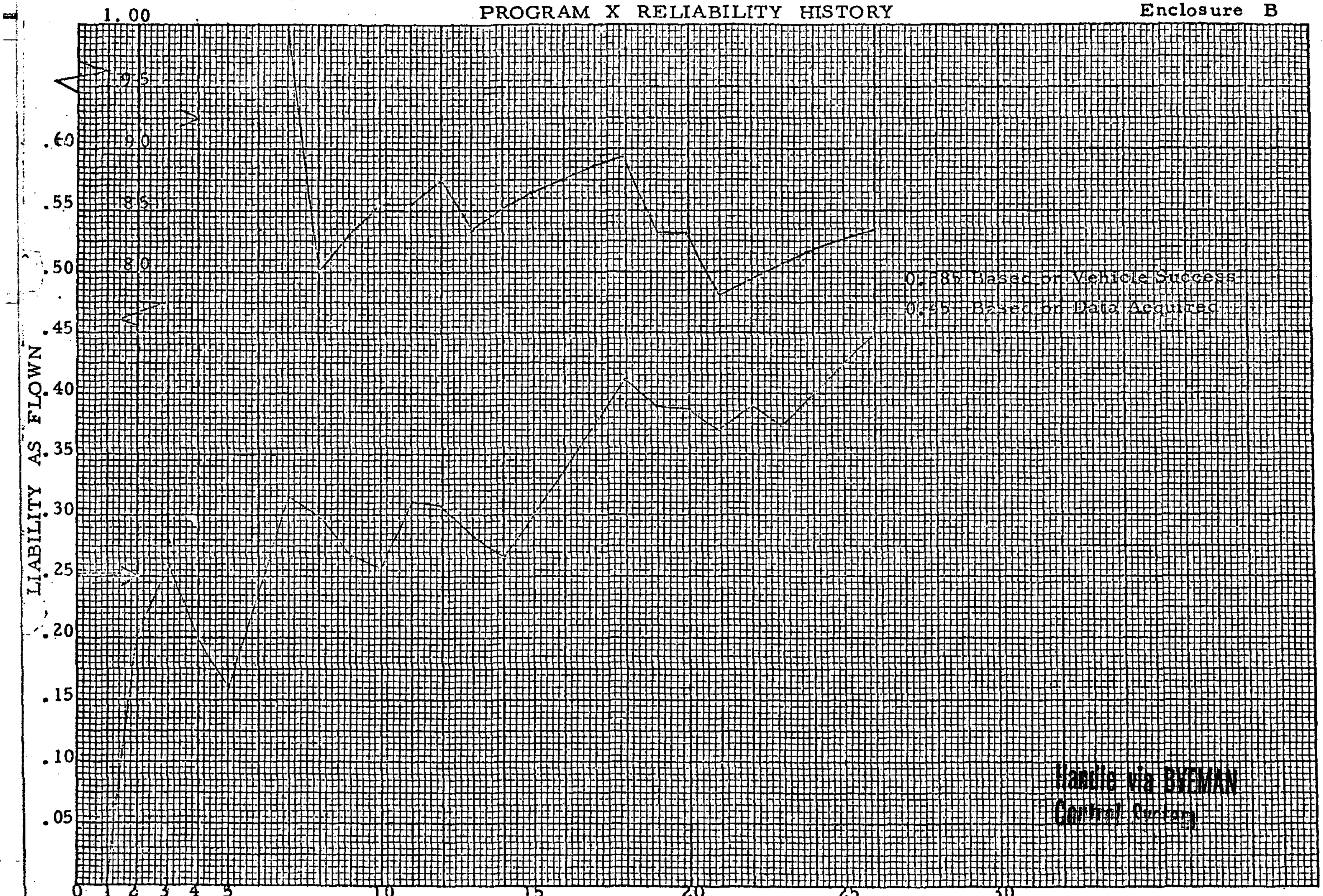
Enclosure B

PROGRAM X RELIABILITY HISTORY



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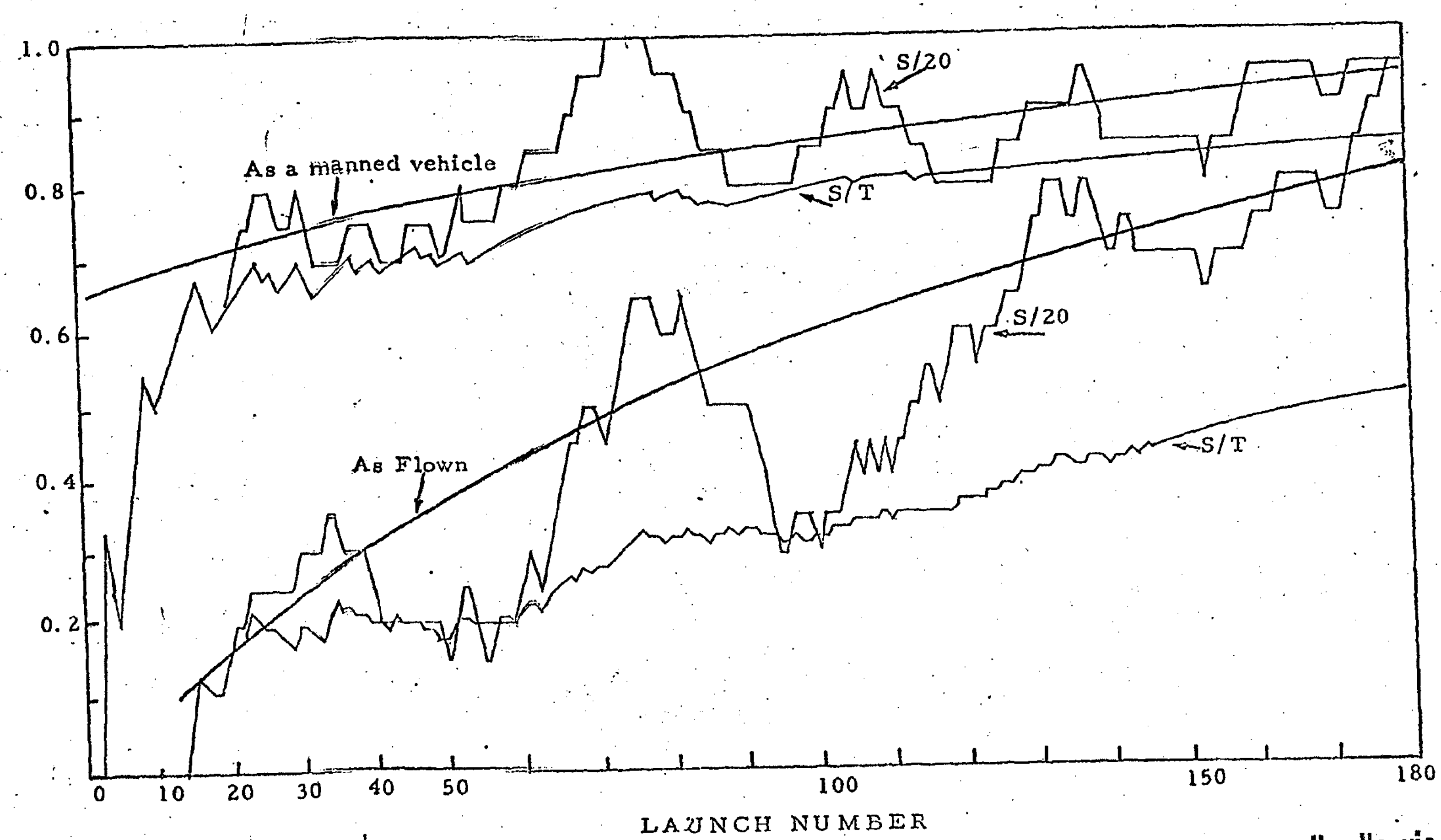
AGENA HISTORY



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MERCURY HISTORY

No.	Vehicle No.	Orbit Achieved / Orbit Planned	Data Acquired	COMMENTS - UNMANNED SPACECRAFT		
				Catastrophic Failure	Orbit	Data Acquired
1	MA-6	3/3	100 %	1 - loss of left yaw jet 2 - manual re-entry -no fuel 3 - thrusters lost/limit switch	2 3	0
2	MA-7	3/3	100	1 - manual re-entry- no horizon scanner	3	0
3	MA-8	6/6	100	None		100%
4	MA-9	22/22	100	1 - ACS/programmer 2 - power supply for controls 3 - power supply - short in control system	11 19 19	0

Manned - 100 % Unmanned - 25 %

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Enclosure E

GEMINI A HISTORY

No.	Vehicle No.	Orbit Achieved / Orbit Planned	Data Acquired	COMMENTS - UNMANNED SPACECRAFT: Catastrophic Failure	Orbit	Data Acquired
1	GT-3	3/3	100 %	1 - IGS nav. errors due to horizon sensor 2 - DC-DC converter short	0 0	0 0
2	GT-4	62/62	100	1 - IGS computer malfunction manual re-entry necessary 2 - ACS had broken wire in electronics	49 62 (re-entry)	0
3	GT-5	121/121	100	9 - malfunctions would cause considerable degradation	4, 36, 75, 51, 25, 1	50%
4	GT-6	17/17	100	1 - instrumentation-tape rec. 2 - electrical syst. -pyro initiators 3 - instrumentation & rec. syst. -multiplier failed mission degraded	13 17 (re-entry) 1	50%
5	GT-7	219/219	100	1 - electrical power breaker out-operated manually 2 - fuel cell degradation 3 - OAMS-yaw left drift	22 19, 23, 25	0-50%
6	GT-8	7/48	40	1 - OAMS - thruster open		0

Manned - 90 % Unmanned - 25 %

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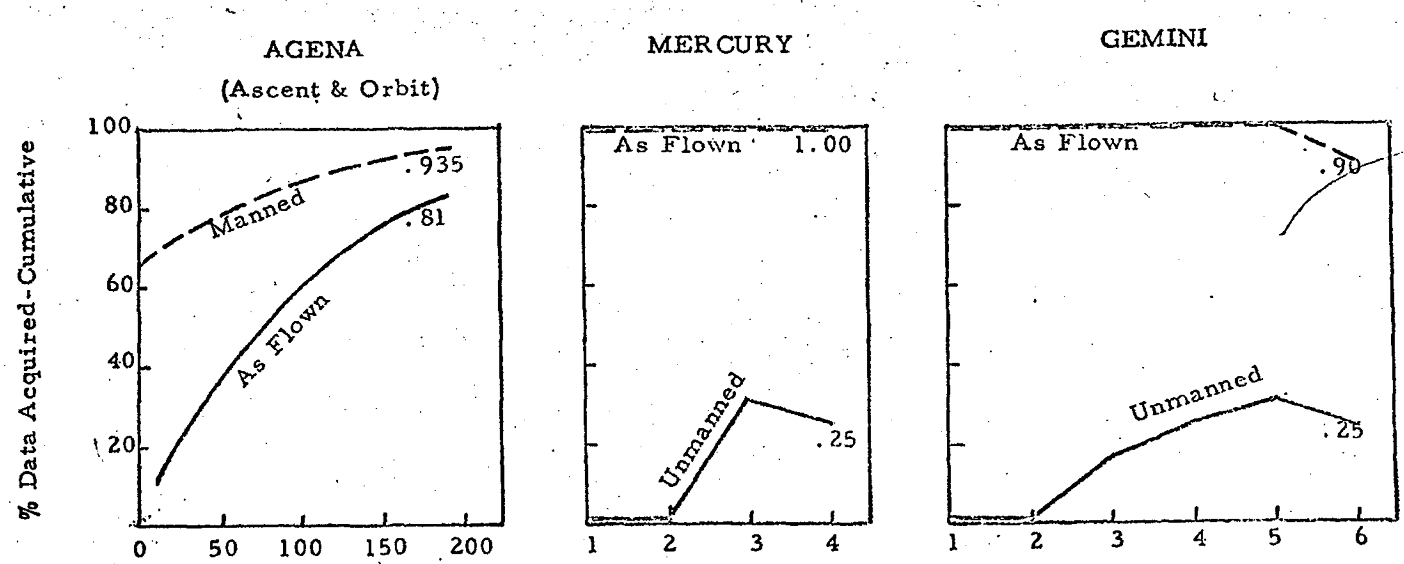
Enclosure F

SPECIAL HANDLING

PERCENT DATA ACQUIRED

FOR MANNED/UNMANNED VEHICLES



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Enclosure G

EXPECTED FAILURES PER DAY

PROGRAM	TOTAL ORBITS	DAYS	FLIGHTS	MAJOR ANOMALIES	ANOMALIES/ DAY	AEG
Agena	?		180 (11 nt)	71		
X	?		24 (3 nt)	33		6500
Average (UM)						
Mercury	34	2 +	4	17	8.5	10,000
Gemini A	429	27	6	28	1	28,000
Average (M)		14.5	5	22.5	1.5	19,000
MOL M/AM	480	30	1	45 (Est.)	3.3 (Est.)	42,000
DAC Prediction at Maturity					0.25*	

*"Redundancy and Spares Estimate" DAC Document dated 21 April 1966 (EX-66-0000-03889) (S)

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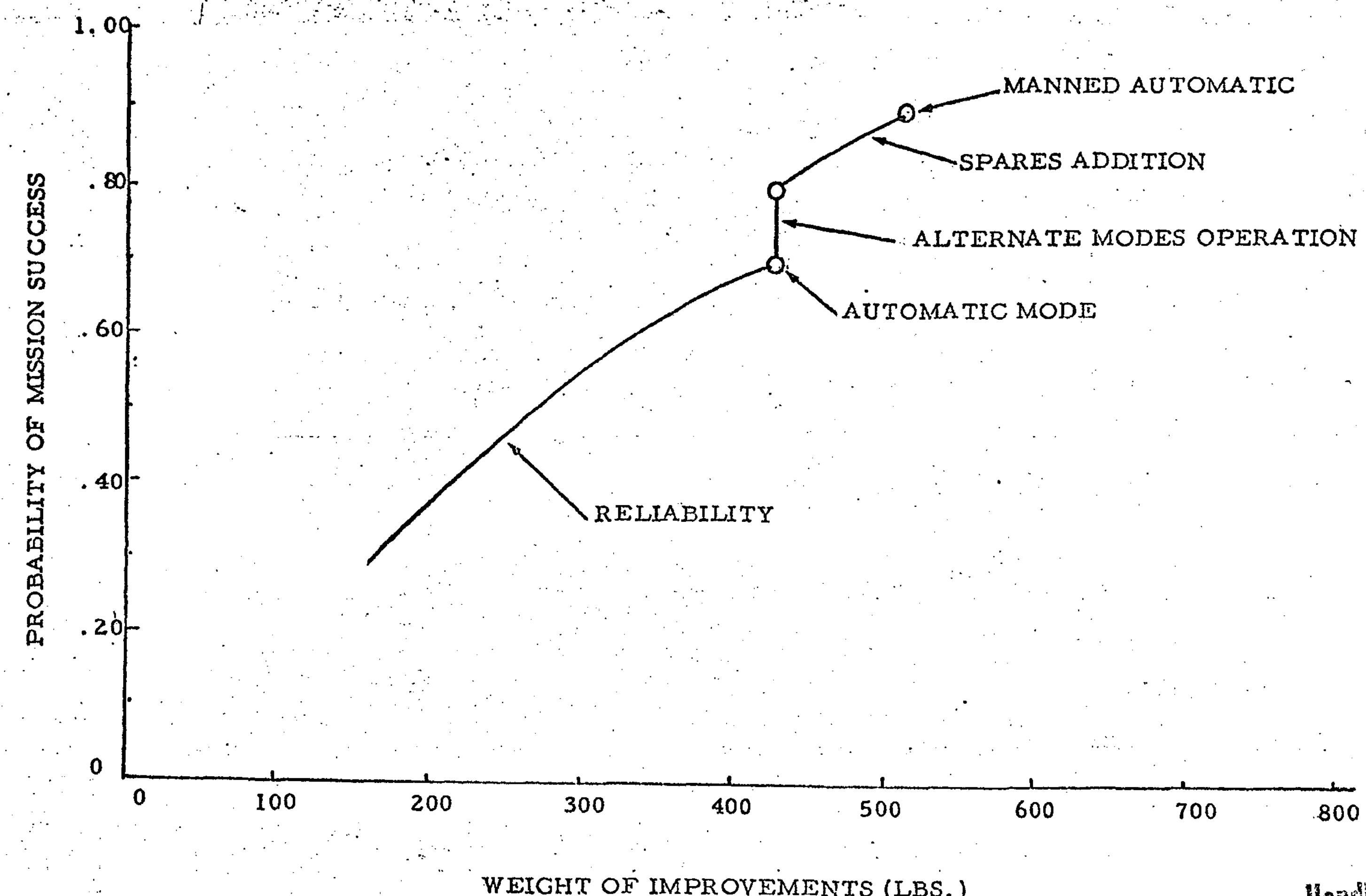
MOL - LABORATORY RELIABILITY
Douglas Aircraft Corporation, 18 March 1966



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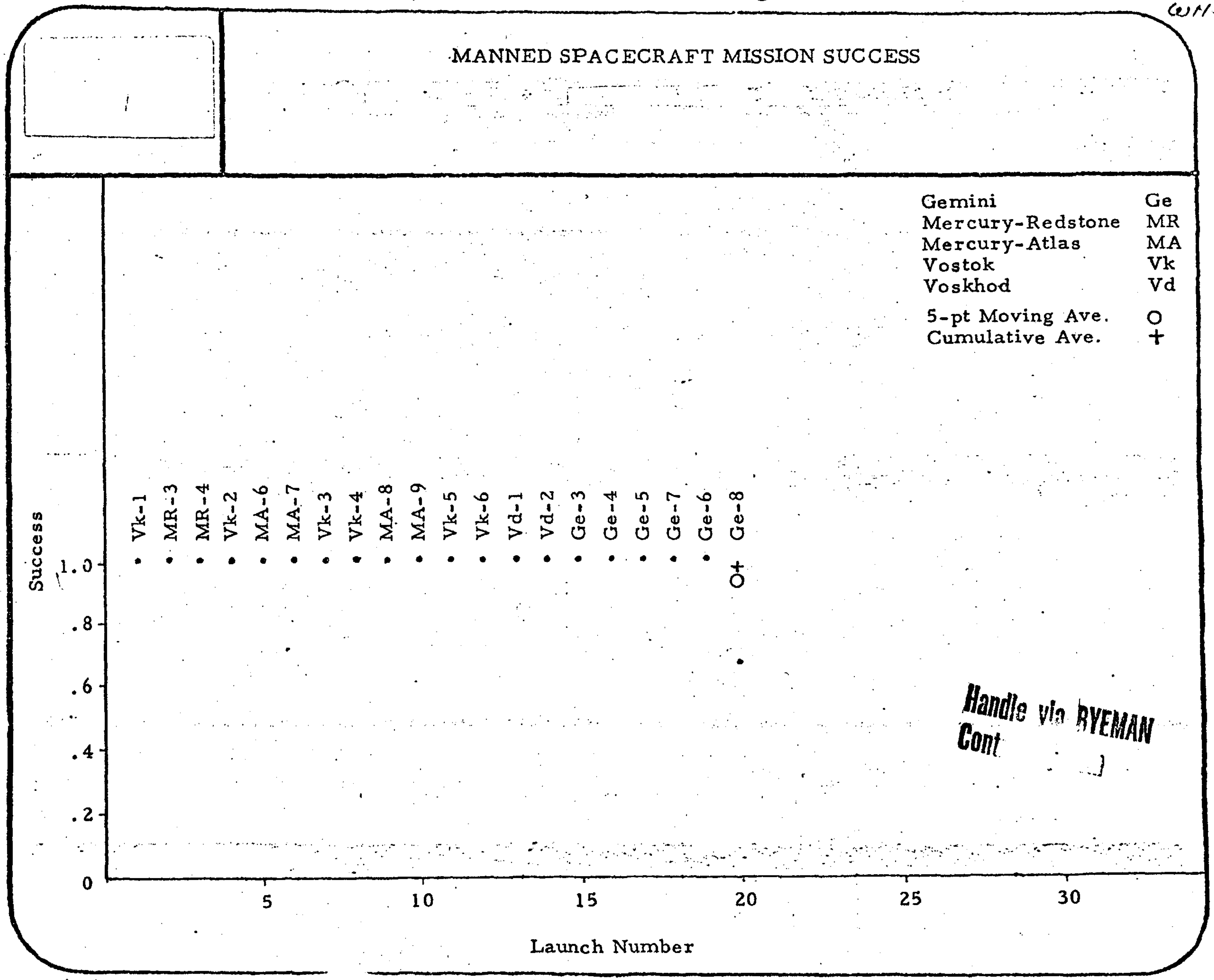
6 May 1966
JRR Enclosure I
WHS-017



only manned flights

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JRR Enclosure J
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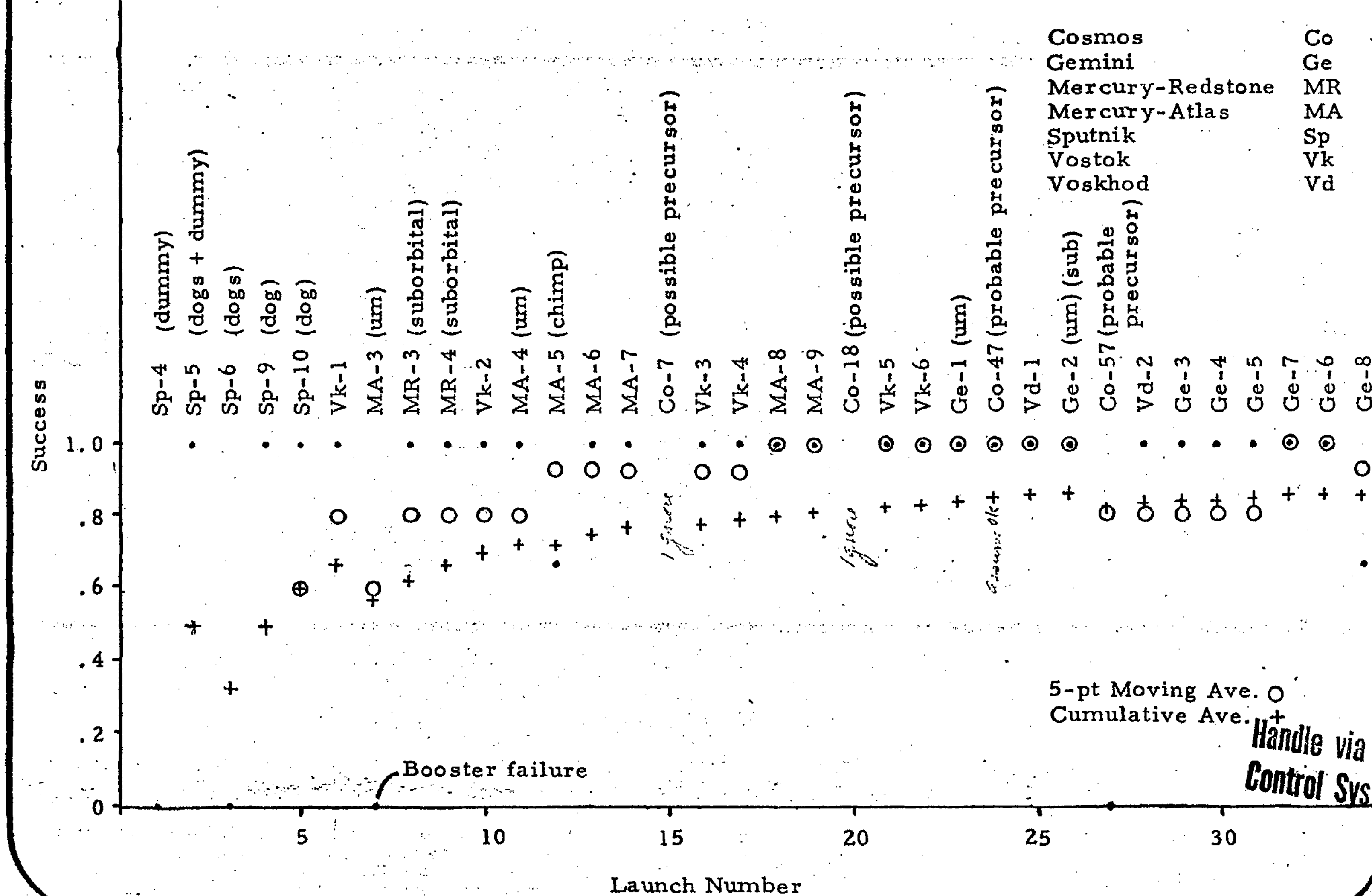
MANNED AND MAN-RATED SPACECRAFT MISSION SUCCESS



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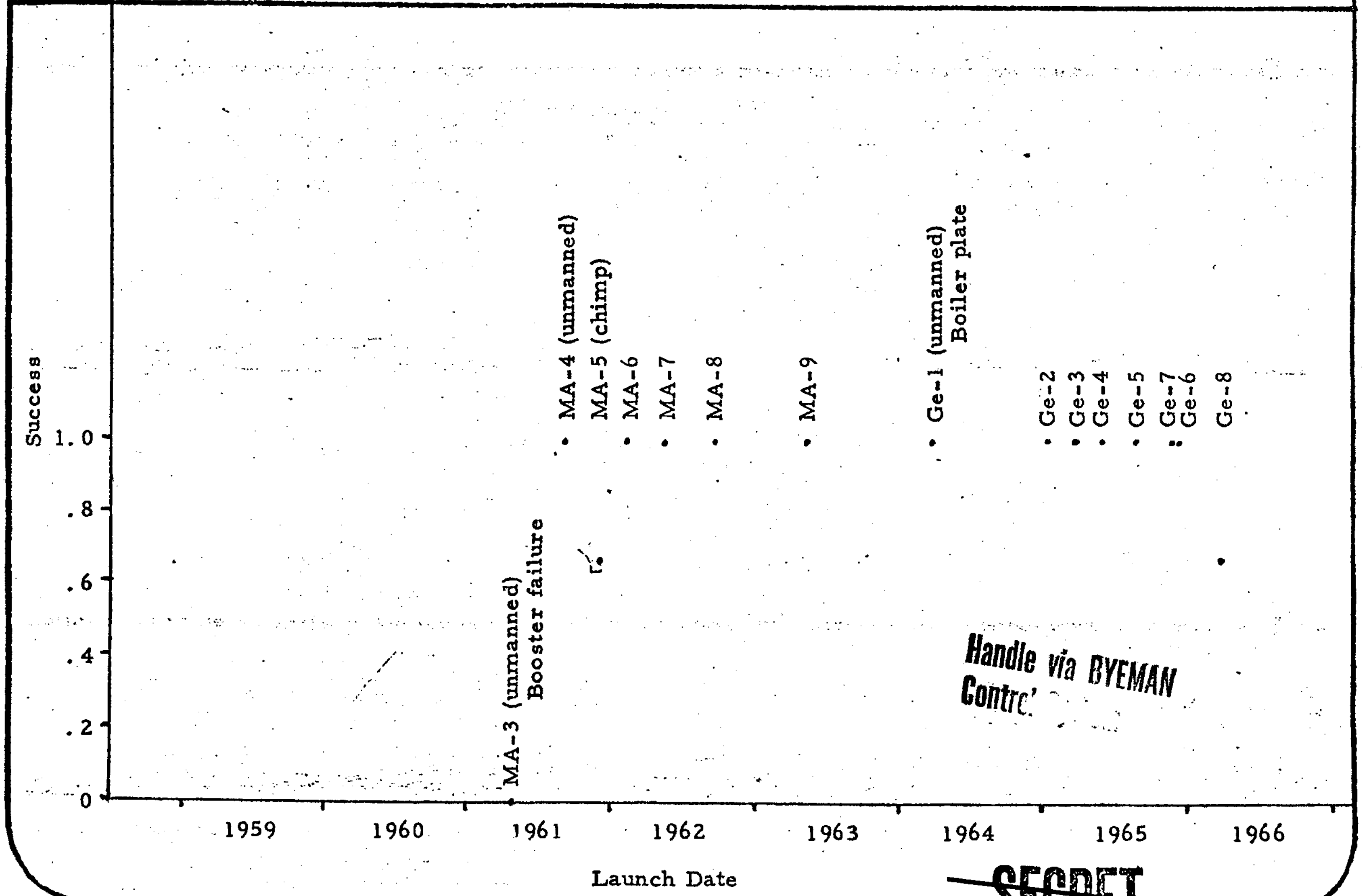
MERCURY-ATLAS AND GEMINI FLIGHTS



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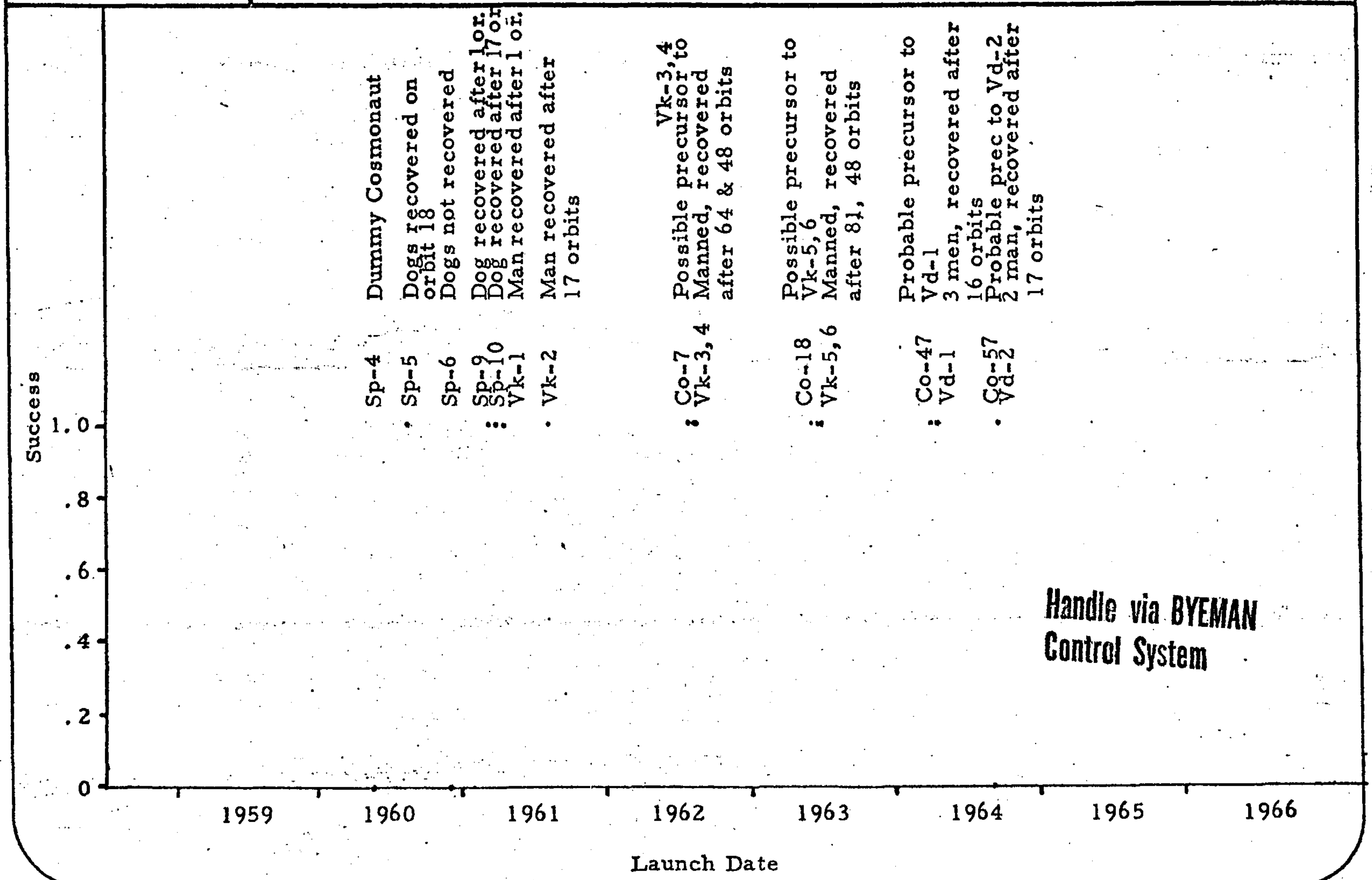
10 May 1966
JRR Enclosure L

WHS-019

SOVIET MANNED SPACE FLIGHTS
AND
PRECEDING QUALIFICATION FLIGHTS



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JRR Enclosure M p.4

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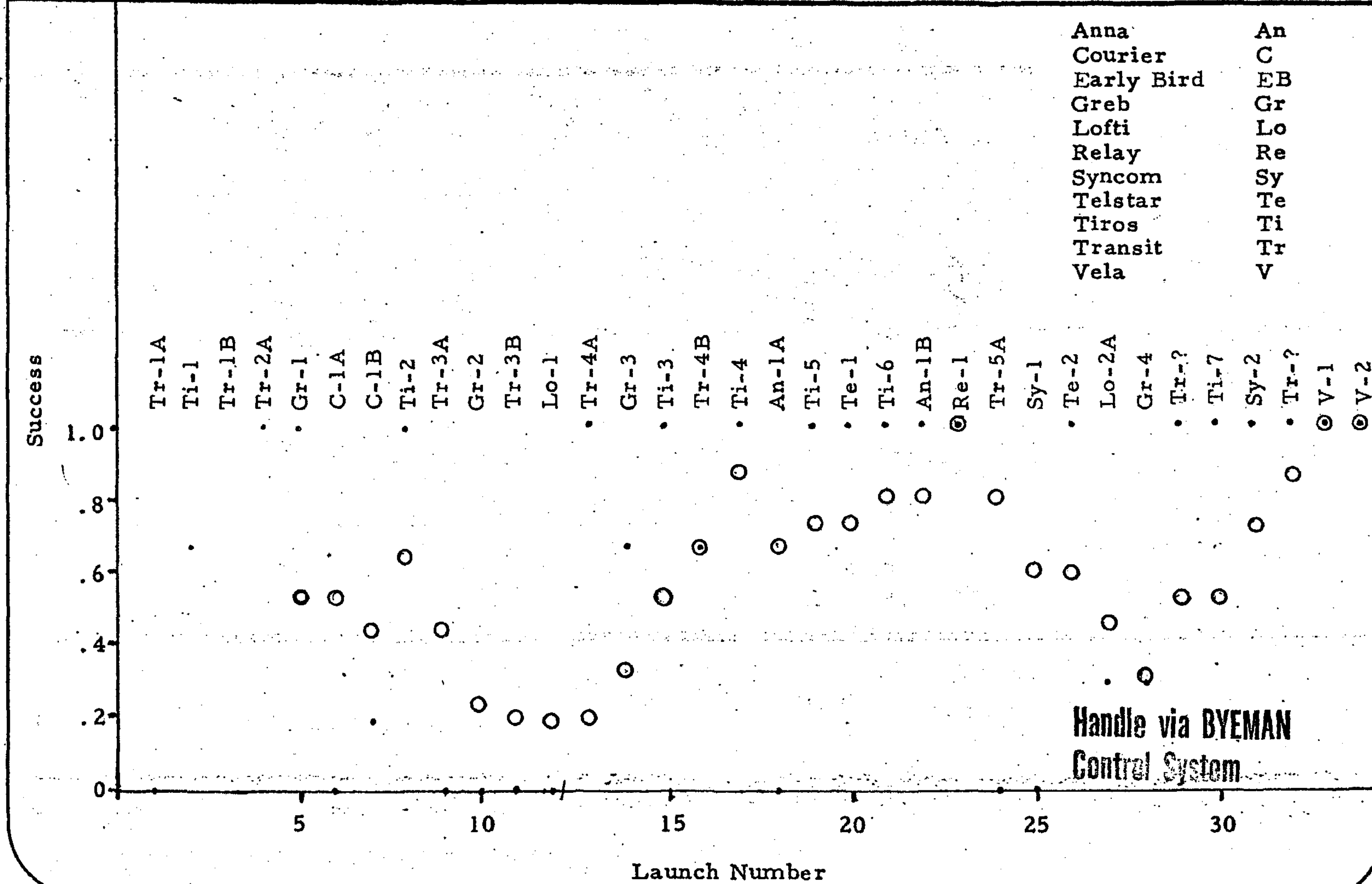
SIMPLE UNMANNED SPACECRAFT MISSION SUCCESS



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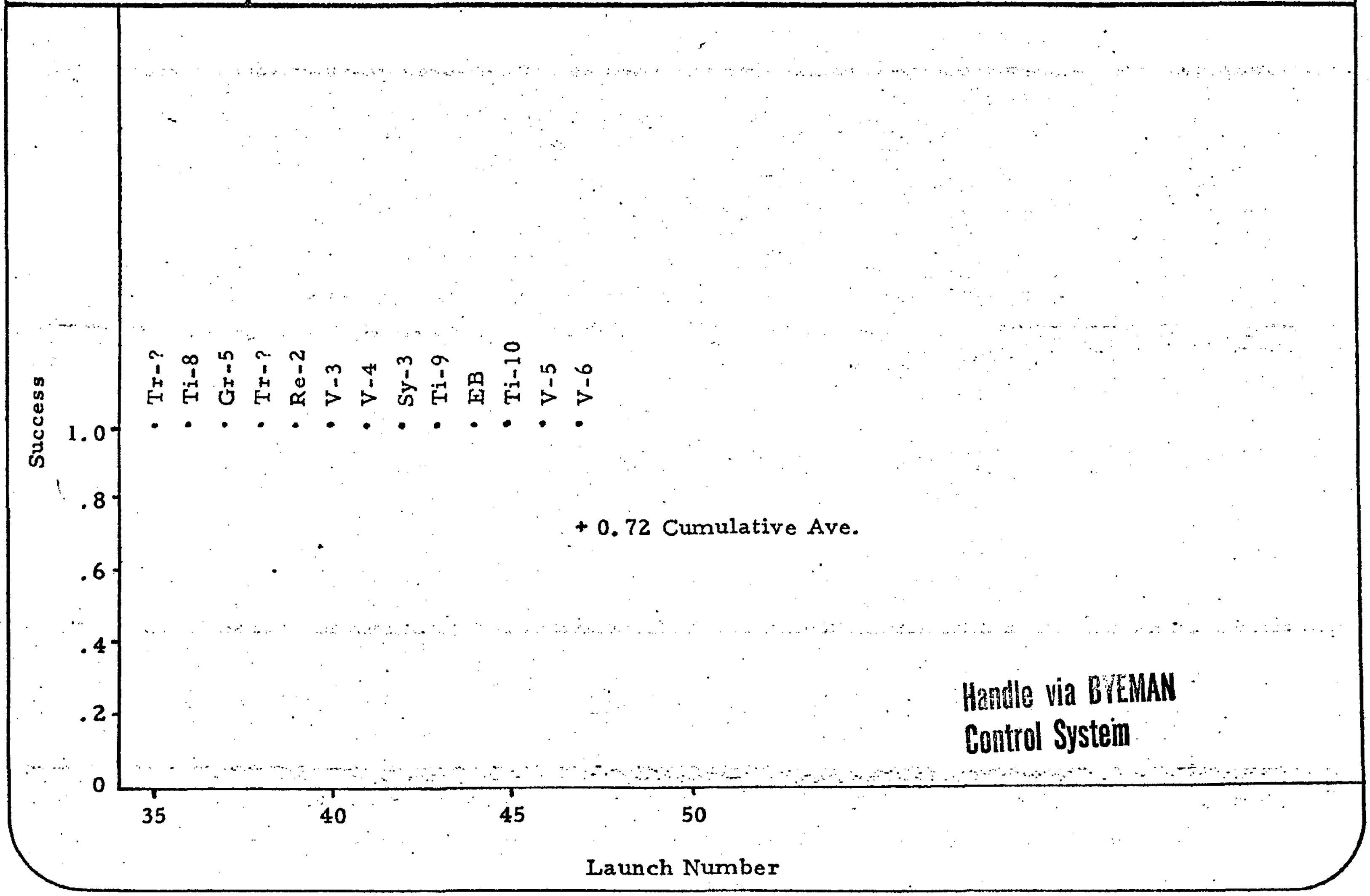
10 May 1966
JRR Enclosure M p.2
WHS-017

SIMPLE UNMANNED SPACECRAFT MISSION SUCCESS
(Continued)



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12 May 1966
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Enclosure N
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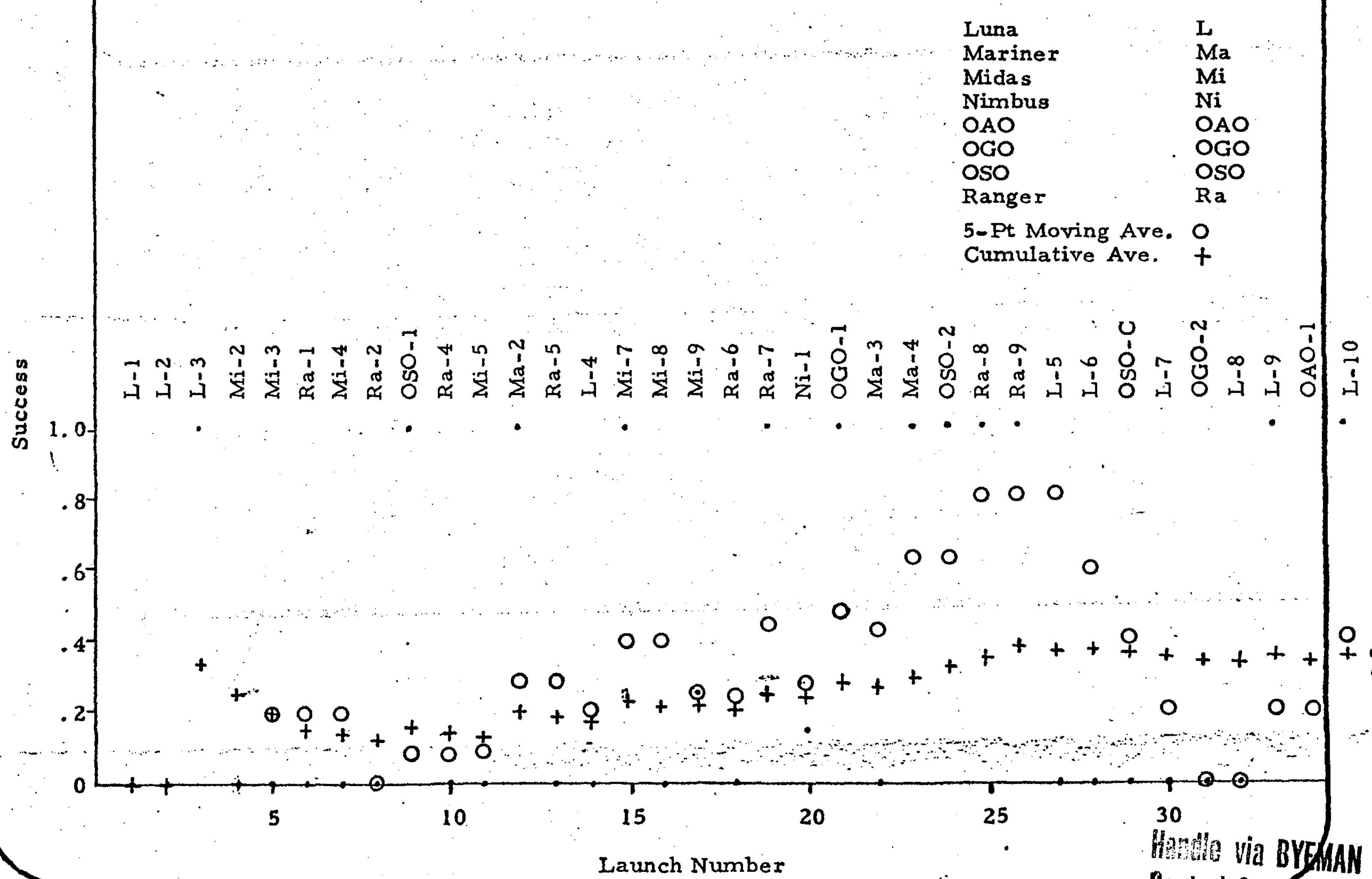
COMPLEX UNMANNED SPACECRAFT MISSION SUCCESS EXCLUDING BOOSTER FAILURES



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JRR Enclosure P

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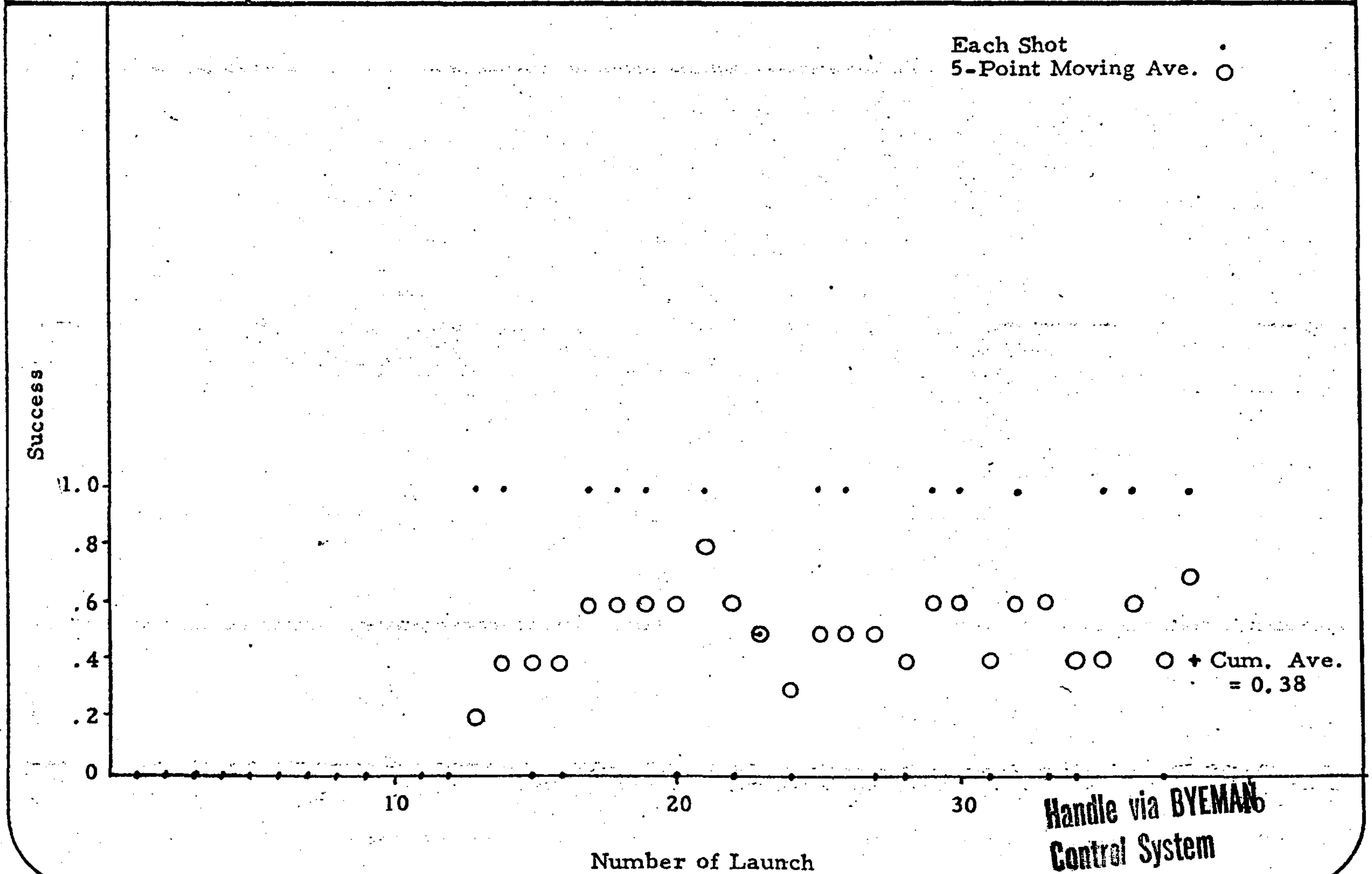
DISCOVERER



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JRR Enclosure Q

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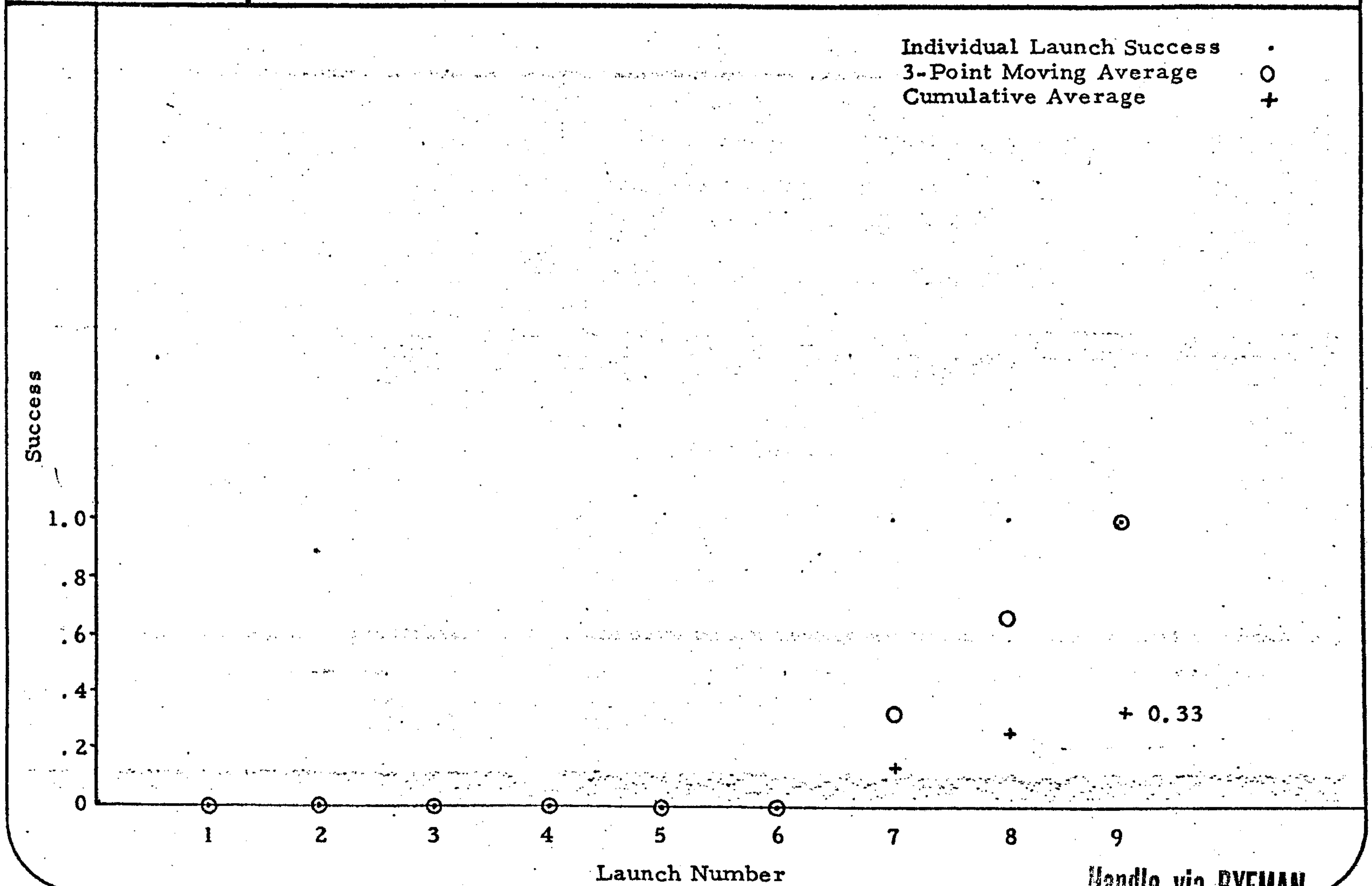
RANGER



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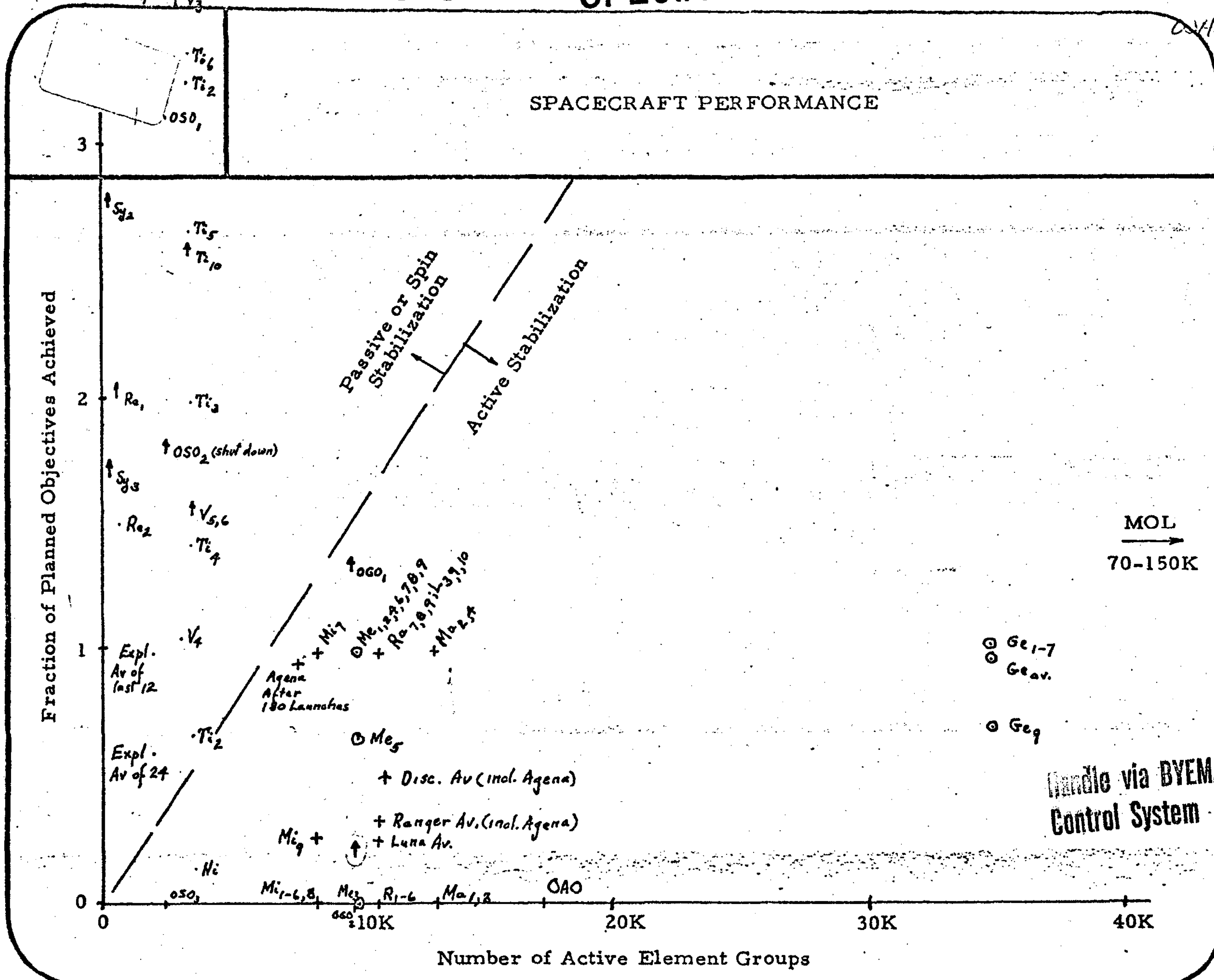
SPACECRAFT PERFORMANCE



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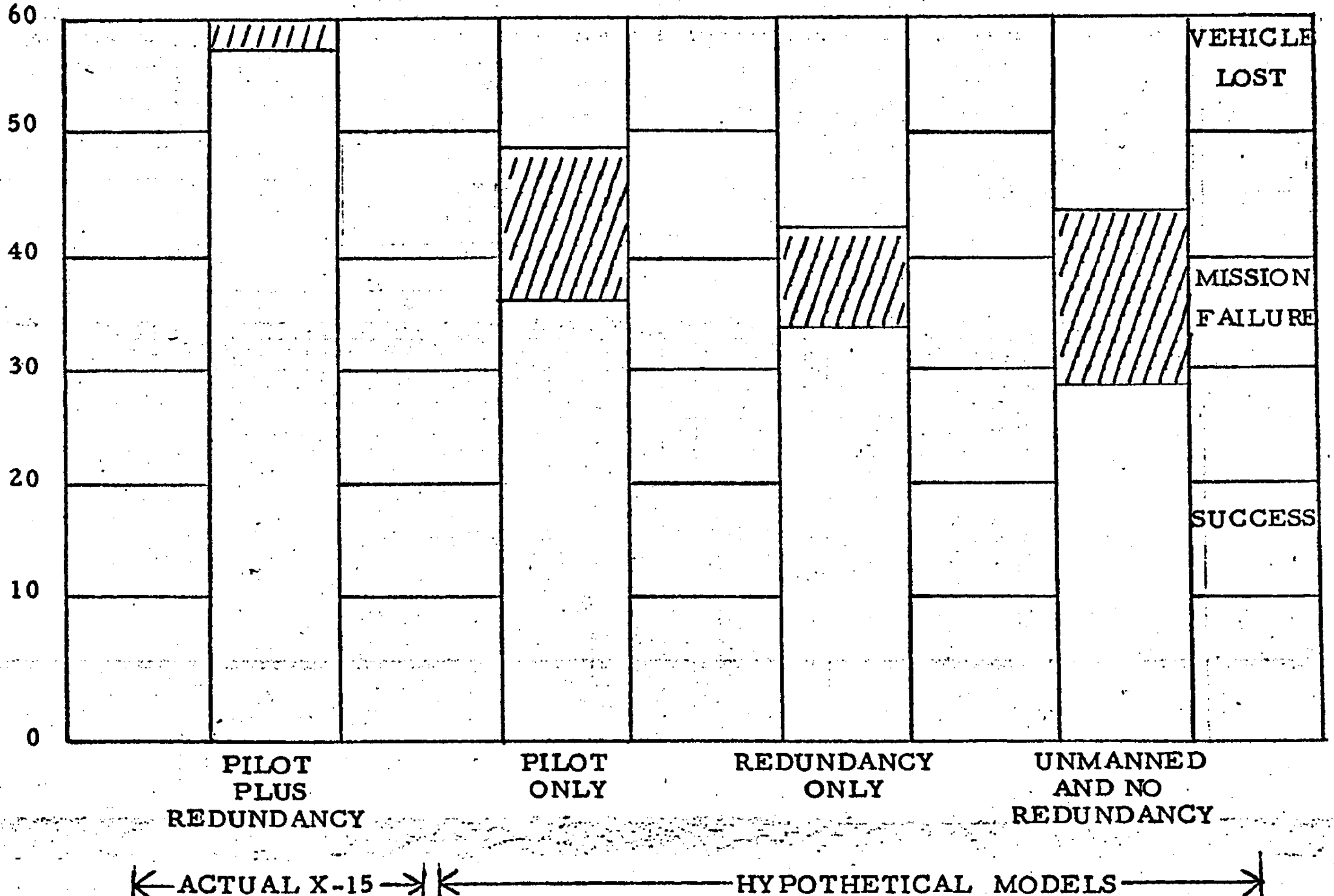
X - 15 PILOT BENEFITS

(THROUGH 1 JULY '62)



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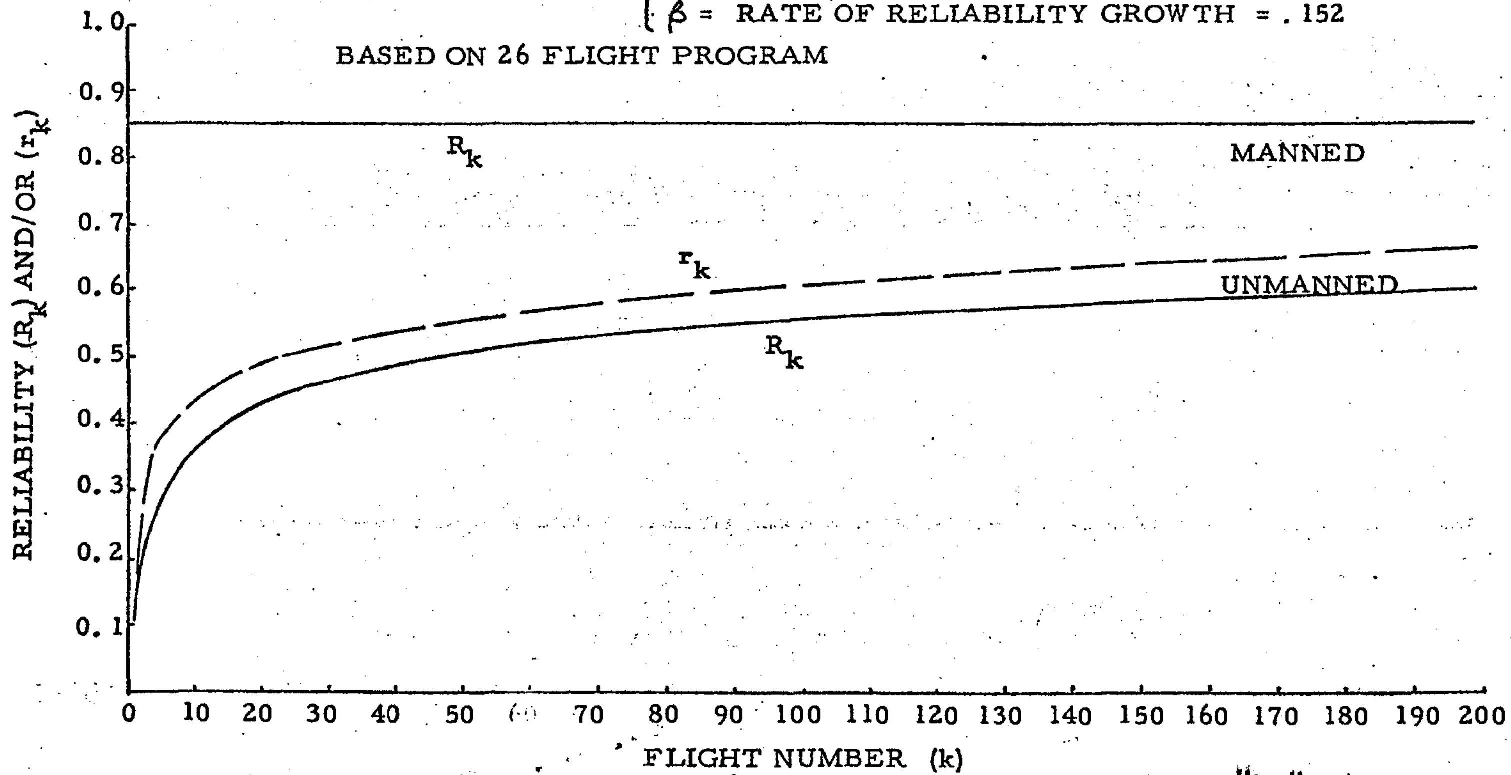
RELIABILITY GROWTH WITH FLIGHT NUMBER
(PROGRAM "X" HISTORY)

R_k = CUMULATIVE RELIABILITY WITH FLIGHT (k)

r_k = RELIABILITY OF FLIGHT (k)

$R_k = 1 - \alpha k^{-\beta}$ $\begin{cases} \alpha = \text{RELIABILITY GROWTH} = .90 \\ \beta = \text{RATE OF RELIABILITY GROWTH} = .152 \end{cases}$

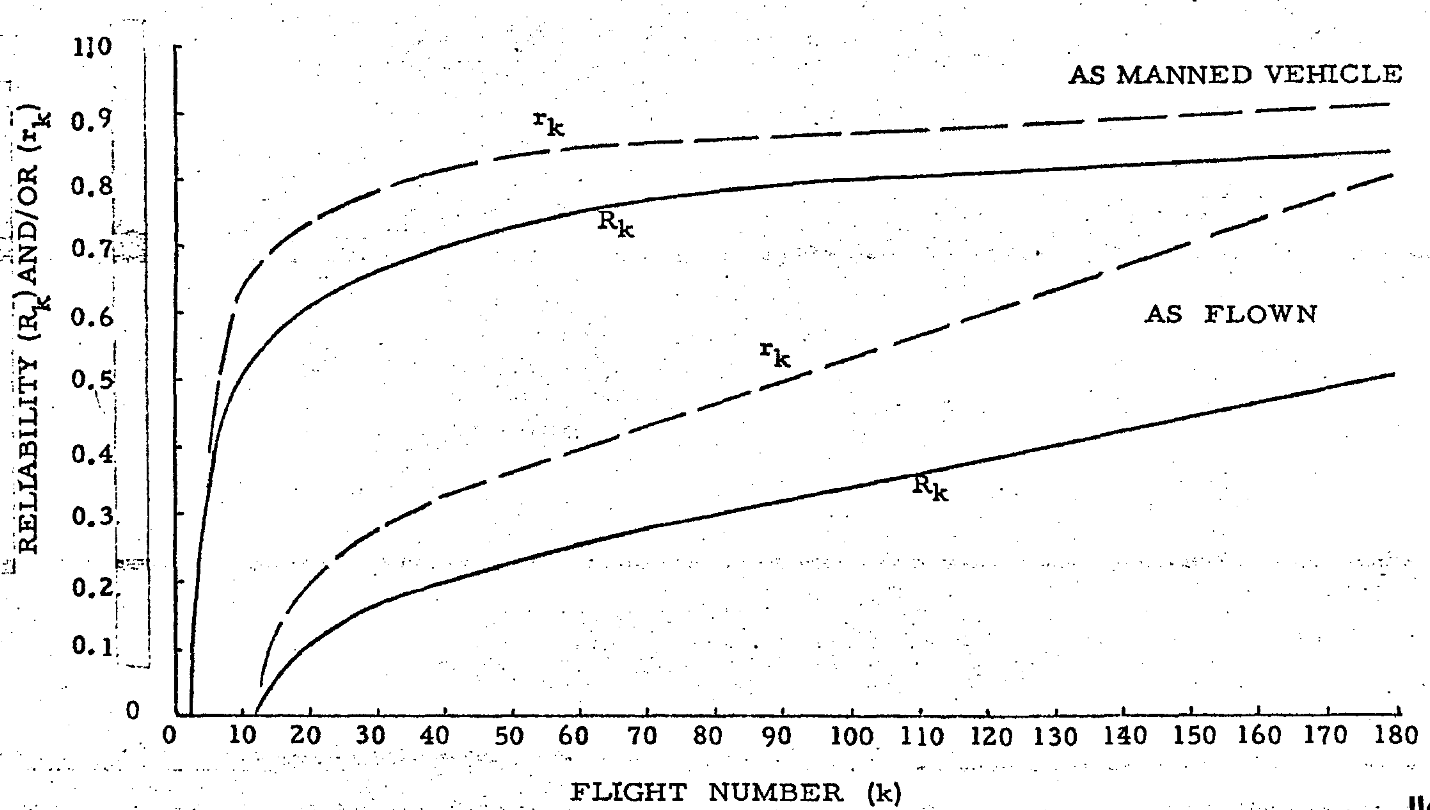
BASED ON 26 FLIGHT PROGRAM



RELIABILITY GROWTH WITH FLIGHT NUMBER
(AGENA HISTORY)

R_k = CUMULATIVE RELIABILITY WITH FLIGHT (k)

r_k = RELIABILITY OF FLIGHT (k)



Enclosure V p.1

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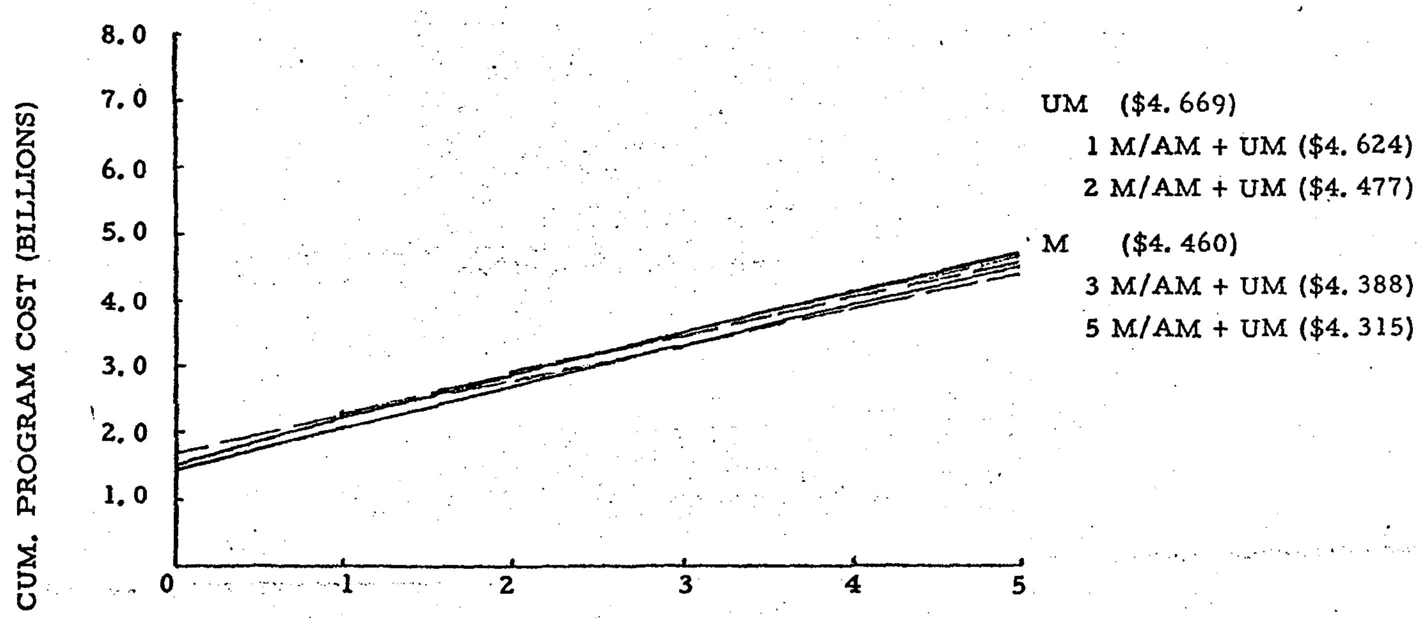
ALTERNATIVE PROGRAM COST SUMMARY
(PROGRAM X BASE)



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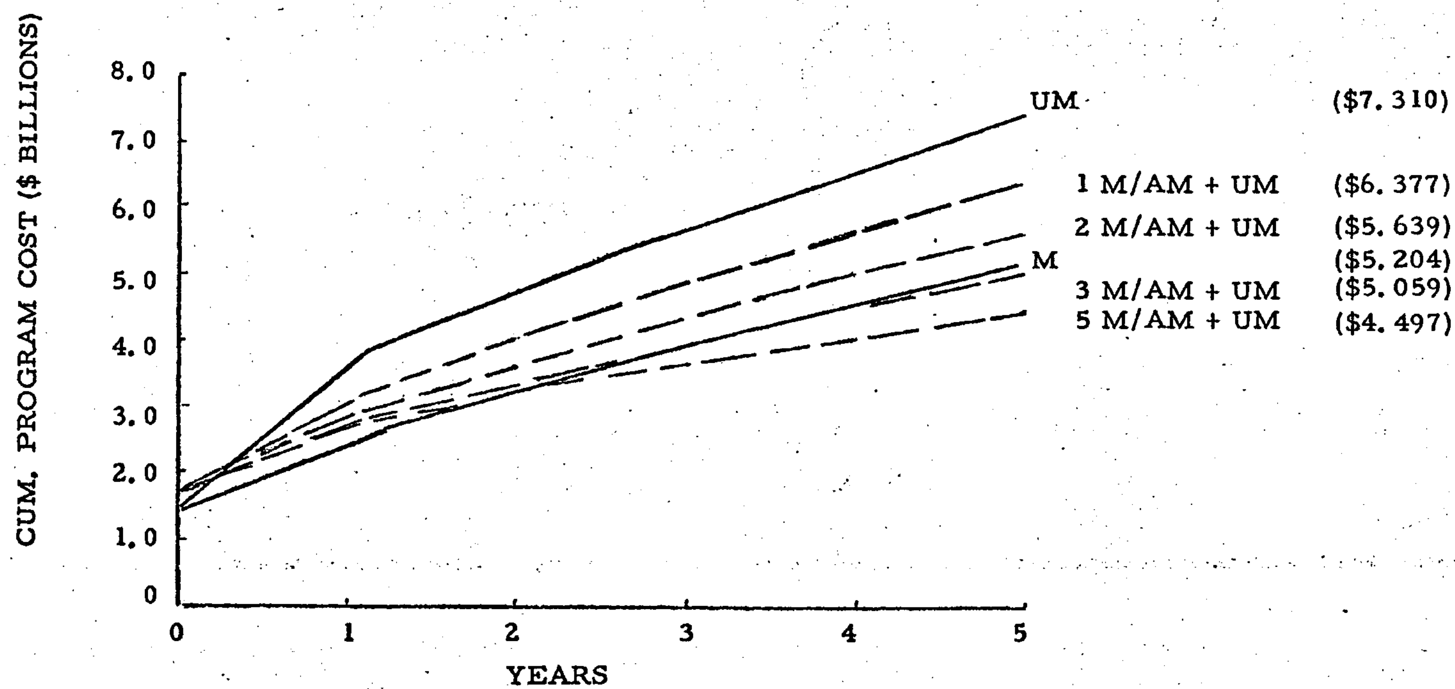
ALTERNATIVE PROGRAM COST SUMMARY
(AGENA BASE)



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