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EXTENDED ION PUMPED VACUUM FRICTION TEST

by

R.L. Hammel

FINAL REPORT

OCTOBER 1971

Prepared for
JET PROPULSION LABORATORY
Pasadena, California 91103

Prepared Under JPL Contract 953123

[redacted]

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

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FOREWORD

This report presents the results of a sliding friction study performed in an ion pumped vacuum facility using test hardware and materials allowing a direct comparison to results previously obtained in orbital and other ground test studies. This work was sponsored by the Jet Propulsion Laboratory under contract 953123. The previous studies were performed for the Air Force Rocket Propulsion Laboratory under contracts AF04611-10747, F04611-69-C-0080, and F04611-70-C-0029 and the Jet Propulsion Laboratory under contract 953123.

The study was conducted by TRW Systems Group, TRW Inc. The primary purpose of the study was to determine the effect of extended sliding on the friction behavior for comparison with that obtained in the earlier test programs.

The JPL Project Manager was Mr. John T. Wang of the Thermal-Vacuum Group headed by Mr. Thomas E. Gindorf, Environmental Requirements Section. Mrs. June Timm of TRW is acknowledged for her activities in performing the data reduction.

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This report has been reviewed and is approved.

ABSTRACT

undary layer friction data under ion pumped vacuum was taken for xteen material couples. The test series was an extension of a previous udy of the effects of modified ion pumped environments. Sliding istances imposed in the present effort greatly exceeded any studied in he previous contiguous, flight or ground tests.

ar out of specific couples, in particular, thin film lubricants was oted. Whereas the previous studies were limited to approximately 120 ters of maximum sliding, sliding in excess of 5000 meters was achieved or some couples.

The behavior of the test hardware including wear out of the mechanisms was noted. As a result, the impact of test interruption was observed for several test couples. Recovery of the friction upon re-establishing sliding in vacuum was generally rapid. The results of the extended sliding study reinforce the previous conclusion that sliding distance (mechanical history) is the primary factor in establishing the force limiting boundary layer friction. General friction values under the extended sliding confirm those observed in previous orbital and the related ground test studies.

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LIST OF ABBREVIATIONS

AFML - Air Force Materials Laboratory
AFRPL - Air Force Rocket Pronulsion Laboratory
AFSL - Air Force Special Lubricant
Ag - Silver
AH - Ampere Hour
Al - Aluminum
Al_2O_3 - Aluminum Oxide
Ar - Argon
atm - Atmosphere
Au - Gold

Be - Beryllium
BN - Boron Nitride

CALIB CKT - Calibration Circuit
CLK & CNTR - Clock and Counter
cm - Centimeter
Co - Cobalt
CO - Carbon Monoxide
CO_2 - Carbon Dioxide
COMP AMP - Compression Amplifier

dc - Direct Current
DC - Dow Corning

ERS - Environmental Research Satellite
ETR - Eastern Test Range

FLTR - Filter
ft - Foot

GE STC - General Electric Space Technology Center
gm - Gram

H_2 - Hydrogen
H_2O - Water
HSKPG - Housekeeping

in - Inch
ISOL - Isolation

JPL - Jet Propulsion Laboratory

K - Kelvin

l - Liter
LN - Liquid Nitrogen
LP - Low Power

MIN PWR - Minimum Power
mol - Molecule
Mol Sink - Molecular Sink
Moltrap - Molecular Trap
MoS_2 - Molybdenum Disulfide
MTR - Motor
μ_k - Coefficient of Friction

n. - Nautical
N_2 - Nitrogen
NASA - National Aeronautics and Space Administration
Nat - Natural
NRC - National Research Corporation

O_2 - Oxygen
OAR - Office of Aerospace Research
ORS - Octahedral Research Satellite
OV - Orbital Vehicle

π - Pi
PTFE - Polytetrafluorethylene

RF - Radio Frequency
RX - Receiver

SCO - Subcarrier Oscillator
sec - Second
Sn - Tin
S.S. - Stainless Steel
STADAN - Space Tracking and Data Acquisition Network
Syn - Synthetic

TEMP - Temperature
TX - Transmitter

UHV - Ultrahigh Vacuum

WC - Tungsten Carbide
WSe_2 - Tungsten Diselenide

ZULU - International Mean Time

I
INTRODUCTION

report presents the results of a sliding friction study in which the fficients of friction over extended sliding distances were determined sixteen material couples. The test hardware and materials were derived a previous orbital test program and were also used in generating eral other sets of comparative ground test vacuum data. In the present st, the test pairs on one module were subjected to over 1000 meters of iding while couples on the other module were tested to over 5000 meters. ear out of the test modules occurred during the extended sliding test ecessitating interruption and repair. Pre-planned alternates in the vent of such an occurrence were used.

This study is the culmination of several previous programs performed by TRW Systems for the Air Force Rocket Propulsion Laboratory and Jet Propulsion Laboratory in surface adhesion mechanics. These studies are directed toward improving the testing of devices, components and sliding contact mechanisms by the establishment and definition of adequate space qualification techniques.

A previous program, AFRPL-TR-69-207 In-Space Friction Test[2], developed a small friction subsatellite design and experiments, manufactured and qualified two satellite systems (ERS 19 and 20) with associated ground test hardware and performed both orbital and ground test experiments of the frictional behavior of sixteen material combinations. Details of the spacecraft system are available in Reference 3, "Environmental Research Satellites for In-space Friction Experiments - System Description Document" and Reference 4, "Operations Plan: Environmental Research Satellite No. 20". Details of the ground test experiment equipment hardware are provided in Reference 5, "AFRPL Ground Test Friction Experiment - Operations Manual".

The orbital test phase was initiated in April 1967 with the launch of ERS 20 from the Eastern Test Range. A planned elliptical orbit ranging from 4600 n. miles perigee to 60,000 n. miles apogee was achieved. Experiment data was acquired over a fourteen-month period at which time the spacecraft test was terminated. As part of the orbital test program, prelaunch data was taken in an oil diffusion pumped ultrahigh vacuum environment prior to initiating the orbital test phase. Additional post launch ground tests were also conducted which included tests to evaluate the effects of ultraviolet radiation, inert gases, oxygen, water vapor, laboratory air and controlled oil vapor contamination. These tests are described in Reference 2.

In 1969 a set of comparative friction data was taken in the JPL Molecular Sink Vacuum Facility. Subsequently, in early 1970 a comparative set of ground friction data was taken in an ion pumped vacuum system as described in Reference 1, Ion Pumped Vacuum Friction, AFRPL-TR-70-120. The results of this study which extends the test initiated in a modified ion vacuum environment (TRW Docu. No. 17805-6001-R0-00) are reviewed in light of both the previous orbital, molecular sink, and ion pumped vacuum friction behavior.

II
BACKGROUND

GENERAL

Over the past six years under sponsorship of the Jet Propulsion oratory and AFRPL, TRW Systems has performed several programs to rease the understanding of space coldwelding and friction processes. luded in these activities were the performance of in-space evaluations hieved by orbiting small special purpose satellites containing experiments secure actual long term space data. Paramount to justifying performing the flight test evaluations has been the use of the orbital data as the sis for performing corollary ground test comparisons and calibrations of simulation facilities. Such ground test studies in conjunction with the orbital data has provided the means to develop criteria allowing the specification of more meaningful standards for testing and qualifying space hardware which involve mechanical motion.

The initial orbital investigation (contract AF 04-611-9883) developed five experimental elements consisting of four Valve Experiments and a Supplemental Contactor Experiment (SCE). These test elements allowed the study of twelve materials combinations under repetitive normal force contact conditions. Two small satellites were designed, fabricated and successfully orbited. Each contained a complement of the five experiment units. Pre and post launch tests in several ground vacuum facilities were accomplished prior to and following the orbital test phase. Extensive orbital test data showed normal force coldwelding to be of a very small magnitude. Contamination effects observed with the SCE allowed a clear-cut differentiation between the test environment produced by several oil diffusion pumped vacuum chambers and an ion pumped facility. The following conclusions regarding purely normal force metal-to-metal contacts were made:

(1) Large numbers of repetitive normal force contacts in the space environment under contact stresses less than yield produced no coldwelding force development of engineering significance.

(2) Dielectric surface contamination buildup which occurred during oil diffusion pumped ground simulation tests was not noted in space nor with an ion pumped ground simulation test. (Such contamination buildup is unacceptable in performing metal-to-metal coldwelding and friction tests.)

(3) No evidence of a space environment exposure time dependence was noted up to integrated orbit times of one year.

(4) No evidence of any orbital altitude dependence was found between 100 and 2000 nautical miles.

The second series of investigations which were undertaken focused upon shear or sliding friction conditions. A modular experiment was designed (AF04-611-9950) to permit sliding eight riders across a similar number of fixed specimens in an oscillatory manner. Subsequently, a special friction satellite design (AF04-611-10747) was developed incorporating two such modules and the necessary command links to permit ground control of the experiment. Two satellites of this design were fabricated. One of these was successfully launched into a 4000 X 65,000 nautical mile orbit. The second was lost during a launch vehicle failure. A photograph of the two friction spacecraft prior to orbital test is shown in Figure 1.

With the successfully launched satellite, orbital friction data was taken over 13 months duration at which time the in-space test was terminated. Following the satellite test program two corollary ground test investigations were accomplished. As part of the earlier orbital friction test program, reference oil pumped ultrahigh vacuum ground tests were performed. These showed a lower friction force development between about one-half of the sixteen pairs tested from that which occurred in space. To resolve this difference a ground test (F04611-C-69-0080) was accomplished in cooperation with the Jet Propulsion Laboratory using their Molecular Sink Vacuum Facility to perform a repetitive set of tests. The Molecular Sink Vacuum Facility embodies advanced design features to produce a unique space vacuum simulation. Following completion of the Mol Sink tests a comparative set of data was also taken in an Ion Pumped (F04611-C-70-0029) Test Facility. The following conclusions have been developed from this

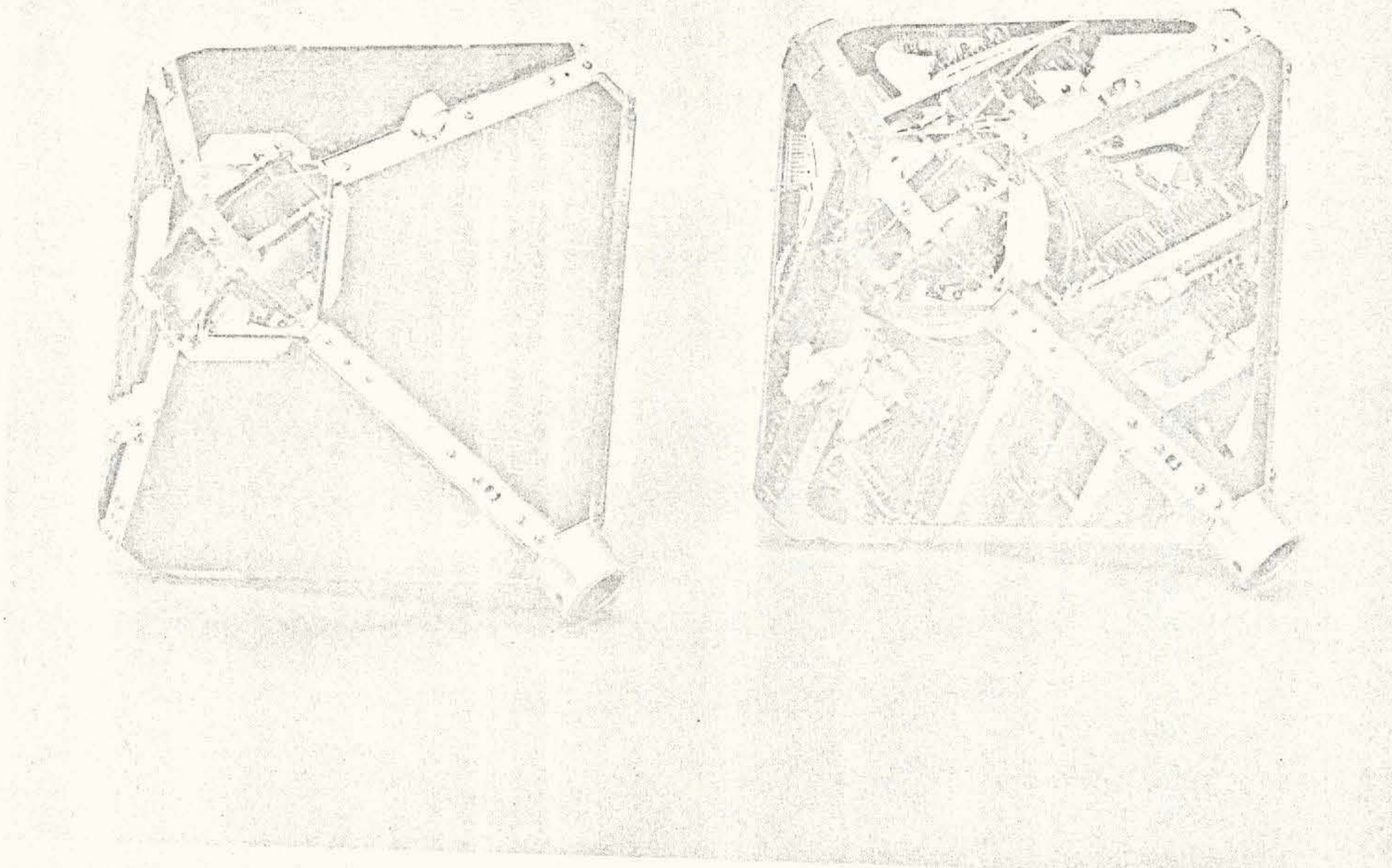


Figure 1. ERS 19 and 20 Friction Spacecraft

series of investigations:

(1) The orbital, Mol Sink and Ion Pumped Friction Data systematically agrees for the sixteen test material pairs tested.

(2) The orbital friction data shows no space exposure time dependence throughout the thirteen-month test phase which included long dwell periods between individual experiment runs.

(3) No orbital altitude dependence was noted.

(4) A systematic lower friction in an oil diffusion pumped ultra-high vacuum occurred for about one-half of the test pairs.

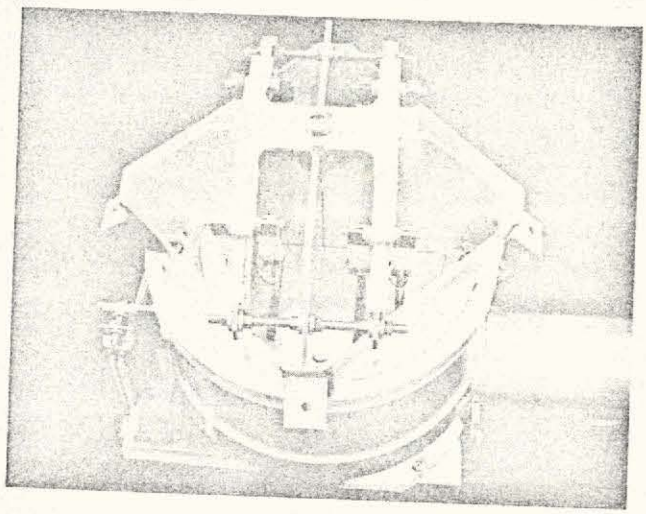
(5) Controlled environment (vacuum degradation studies) in the oil pumped test chamber with water, oxygen, argon and oil showed that those material couples which had lower than the space friction values were virtually insensitive to the degraded vacuum environment. By contrast those couples agreeing with the space data showed a reduction in shear forces under the degraded vacuum studies.

(6) Friction data taken in orbit over thirteen months and in the Mol Sink and Ion Pumped test of ten days showed the accumulated mechanical history to be the dominant factor in establishing the shear force between sliding materials.

2. FRICTION EXPERIMENTS

The experiment consists of two identical units, designated A and B. Each unit contains a drive motor, a mechanical drive assembly, and provisions for making friction measurements on eight individual pairs of material samples. Figures 2 through 5 illustrate one such module. Three sets of modules were built, two for ERS 19 and 20 and one set for performing ground tests.

The experiment was designed to permit direct comparison of results obtained in a laboratory vacuum chamber against in-space conditions, so that more meaningful data may be obtained from future laboratory tests. For this reason, the experiment hardware was designed in a modular method so that identical friction modules could be placed in



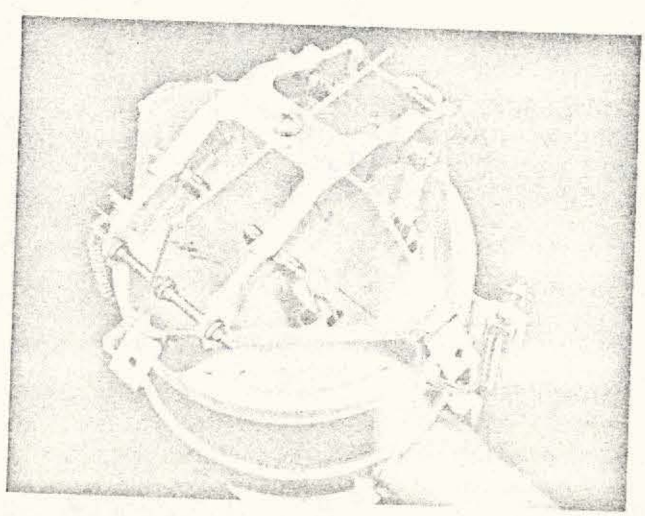


Figure 2. Friction Module

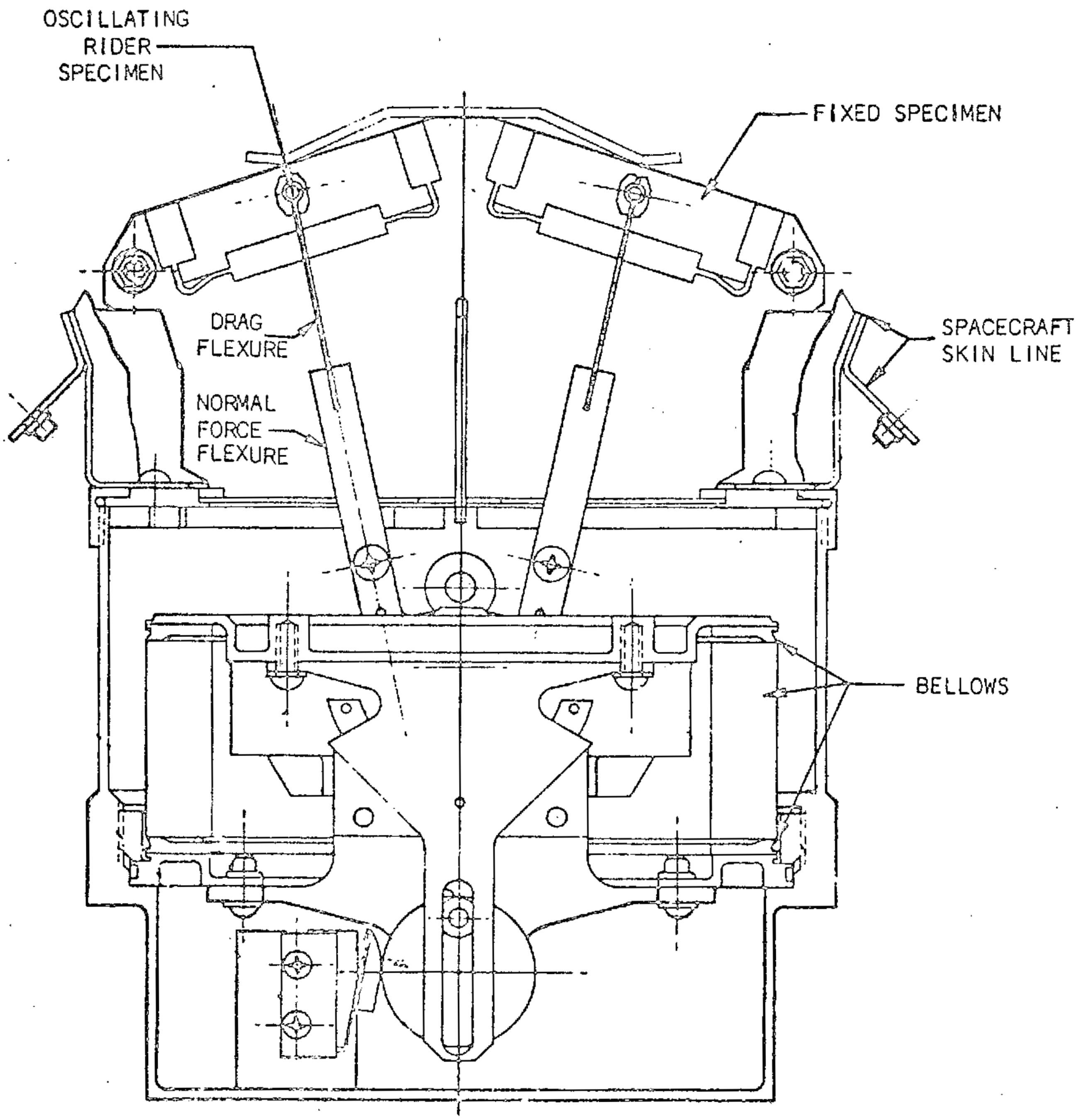


Figure 3 Friction Experiment - Front Cutaway View

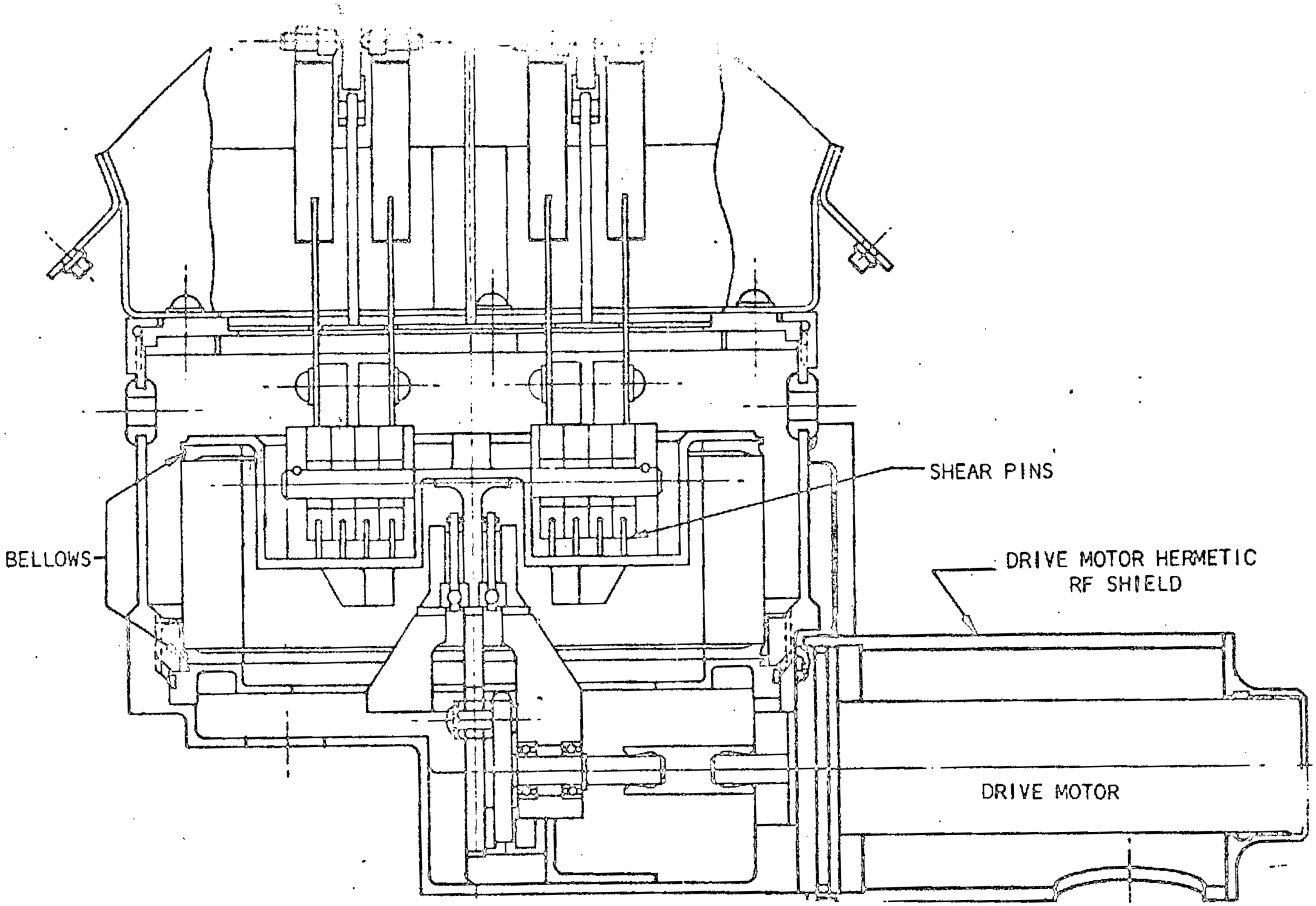


Figure 4 Friction Experiment - Side Cutaway View

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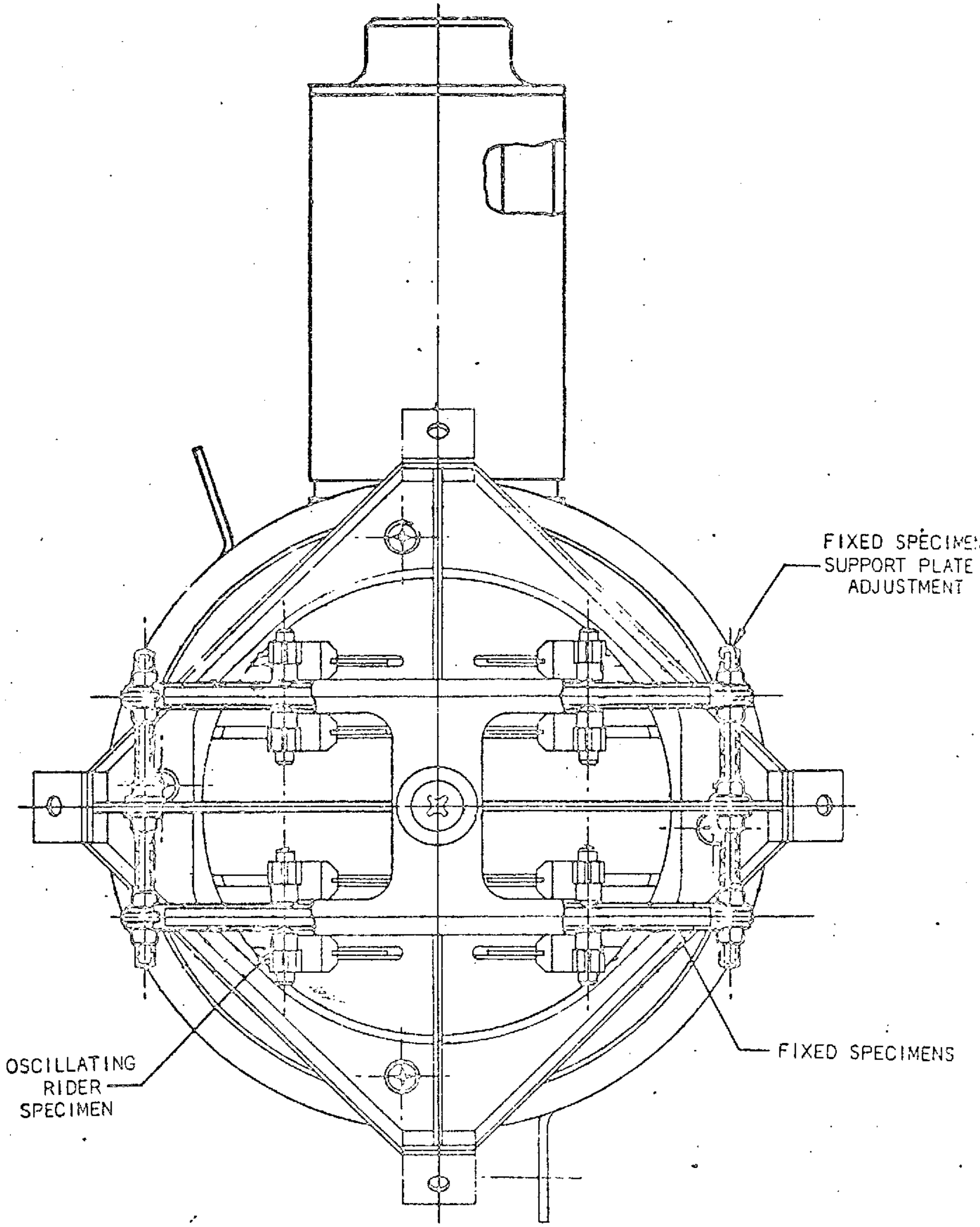

Figure 5 Friction Experiment - Top View

boratory vacuum chamber and in an ERS spacecraft for in-space testing. Important parameters of the investigation are the cumulative number of eriment actuations and the space environmental exposure time.

flight experiment used two friction modules to produce reciprocating iding motion between 16 pairs of frictional surfaces each of a different terial combination. The frictional surfaces were mounted in such a way at they extended out of the ends of the spacecraft and, thereby, derived ximum exposure to the deep vacuum of space, while having maximum olation from outgassing of other spacecraft elements. An individual periment module was commanded "on" through a command receiver link. e of a command link allowing controlled operation assured that the test urfaces were not seriously modified by excessive wear prior to achieving extended orbital exposures. The reciprocating friction specimens and the elemetry commutator were synchronized in order to maximize the ability o analyze the friction data as a function of velocity. The motors, gear trains, and all linkage bearings are hermetically sealed through the use of a bellows assembly and, therefore, the only friction points exposed to vacuum are the test surfaces.

A reciprocating motion was selected in preference to continuous rotary otion for two reasons. The primary advantage is that a range of sliding velocities can be investigated by this technique including zero at each end. In addition, the use of such motion permits the sealing of all working friction surfaces other than the test surfaces.

Elimination of cross-contamination is achieved by incorporating shielding within each module plus utilization of the satellite itself for shielding purposes. Cross-contamination problems are somewhat easier to treat in space than in the laboratory. In space, one need only be concerned with shielding line-of-sight paths from primary or secondary surfaces associated with the origin of the contaminants. The experimental surfaces cannot receive a cross-contamination flux from the solid angle of space which they view. In the laboratory, this same solid angle becomes an acceptance angle for receiving contaminants arising or returning from the inner surfaces of a vacuum chamber.

A key element in the experiment design is the reciprocating arm that holds each moving test specimen. As shown in Figure 6, this arm includes two mutually perpendicular flexures. The "frictional drag" flexure supports two strain gages for indicating the amount of frictional drag which is proportional to the degree of flexing. The output of these gages is telemetered during the flight test. The "normal force" flexure allows application of the normal force to the test specimen surfaces. Strain gages mounted on this flexure allow for setting the magnitude of the normal force. Adjustment of the normal force is made at the rider specimen holder. The flexure assembly is designed with an overload release function that will prevent stoppage of the module drive mechanism due to total seizure of any pair of test materials. This is accomplished by utilizing a shear-pin connection which yields if the coefficient of friction between two samples increases beyond several hundred grams.

The strain gages and their bonding agents were directly exposed to the space environment and, therefore, had to be capable of withstanding direct radiation and solar heating and still meet the performance requirements. Because of their immediate proximity to the friction test surfaces they further could not generate objectionable outgassing contaminants. A satisfactory mounting was developed using a high temperature epoxy (BR 600) which was thermal-vacuum preconditioned at 250°F after gage installation.

Figure 7 shows a logarithmic plot of force versus amplifier output for epoxy-mounted drag flexure gages. This particular flexure is a (-2) configuration having a thickness of .016 inches and represents the design used with the lower coefficient of friction materials. A (-3) configuration which is not shown, has a .020 inch thickness and is employed with higher force friction combinations. Aside from the thickness of the drag flexure, both configurations are identical.

The 3.0 volts amplifier output represen[illegible] center value for the SCO-telemetry input. Use of a double-ended [illegible]ferential log amplifier permits following both directions of the friction force during a specimen traverse with nearly constant accuracy throughout the dynamic force range of interest. Tests on the amplifier showed that within a range of 10° to 40°C, the output voltage changes a maximum of 5 mv.

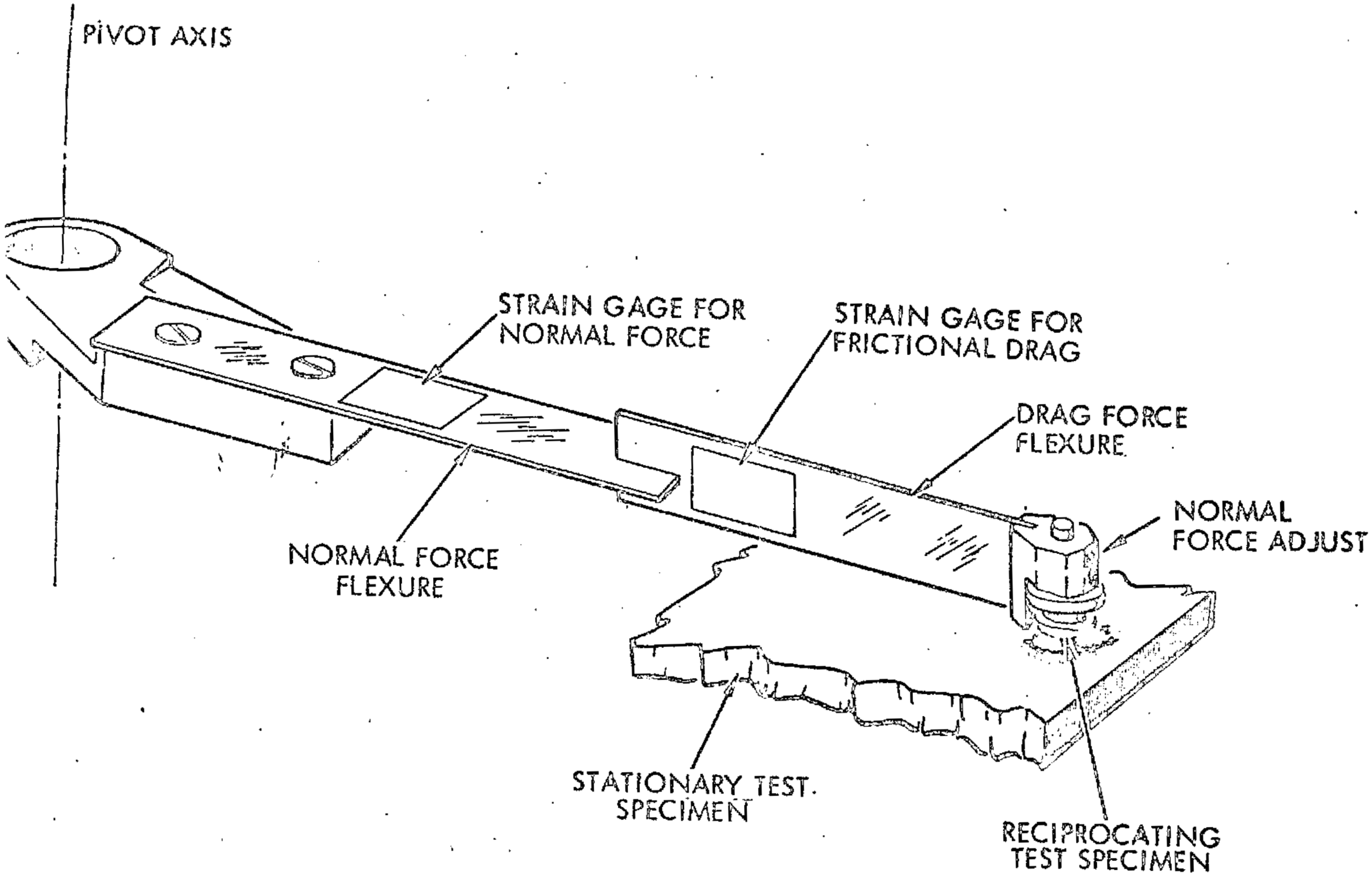

Figure 6 Friction Experiment Compound Flexure

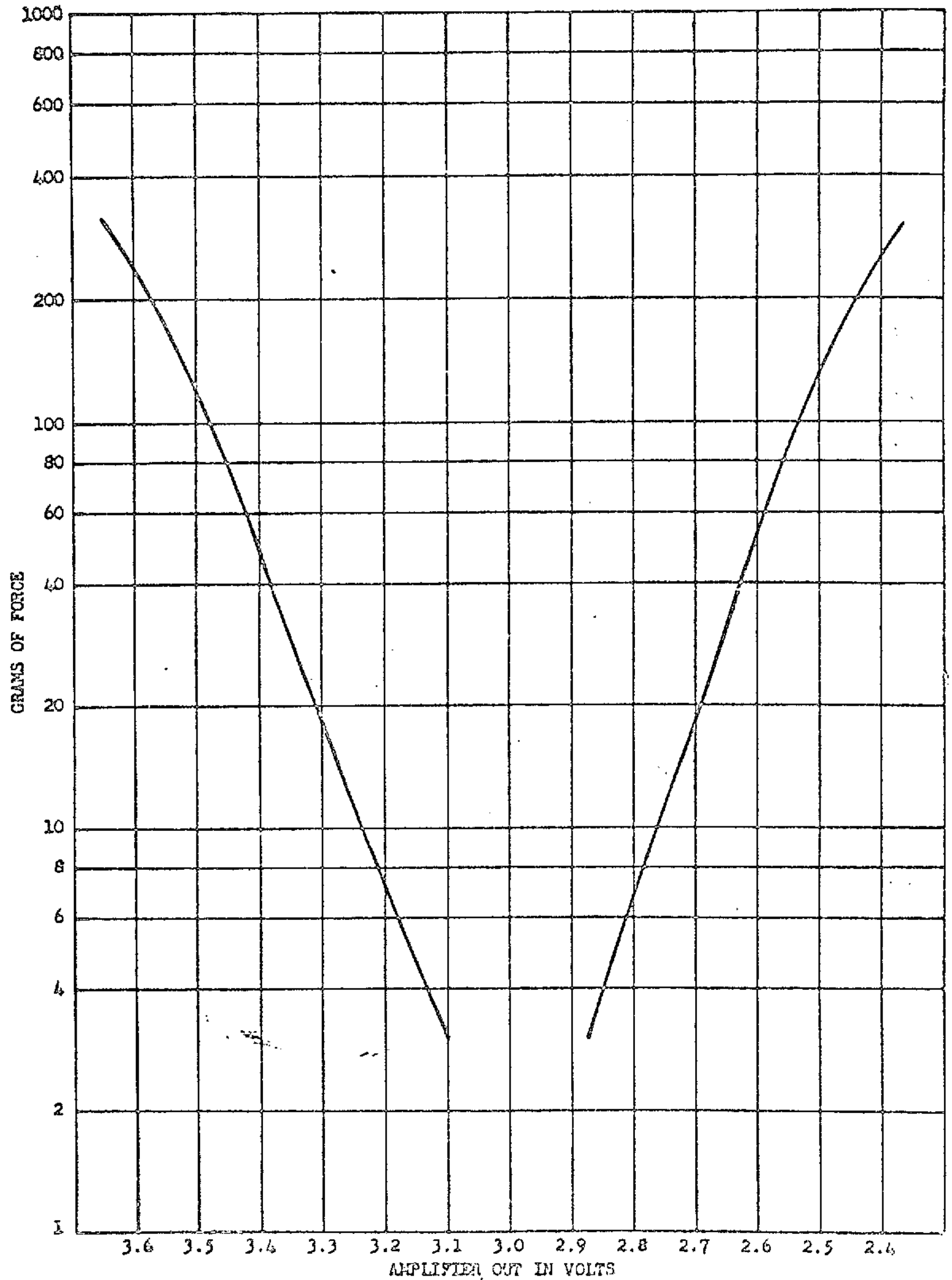

Figure 7 Illustrative Strain Gage and Amplifier Output Versus Inout

The satellite served as a vehicle in which to place the experiment in an earth orbit, thus providing the environmental exposure and measurement periods desired. The satellite system provided for remote control of the experiment and transmission of the resulting data to a ground control station.

The satellite may be considered as being composed of an experiment and the following four subsystems:

1. Command and Control
2. Beacon, Telemetry, and Signal Processing
3. Electrical Power
4. Mechanical

These subsystems are fully described in the Satellite Description Document, Reference 3.

3. GROUND TEST HARDWARE

As previously described, two complete ERS satellite systems (ERS 19 and 20) with friction experiments were built. In conjunction with the satellite design development, breadboard electronics were fabricated. These breadboard electronics in conjunction with two additional experiment modules (Figure 8) provide the hardware to perform laboratory friction tests in simulated space vacuum environments.

The major elements consist of:

a. Two Experiment Modules (A and B)
b. One Breadboard Electronics Rack
c. One Command and Segment Selector Box
d. One Normal Force Test Box

The recorder, power supply, and digital voltmeter equipment used in an actual test setup are standard electronics equipment.

An expanded description of the ground test hardware and its operation is contained in Reference 4. A typical experiment setup is shown by the interconnect diagram, Figure 9.

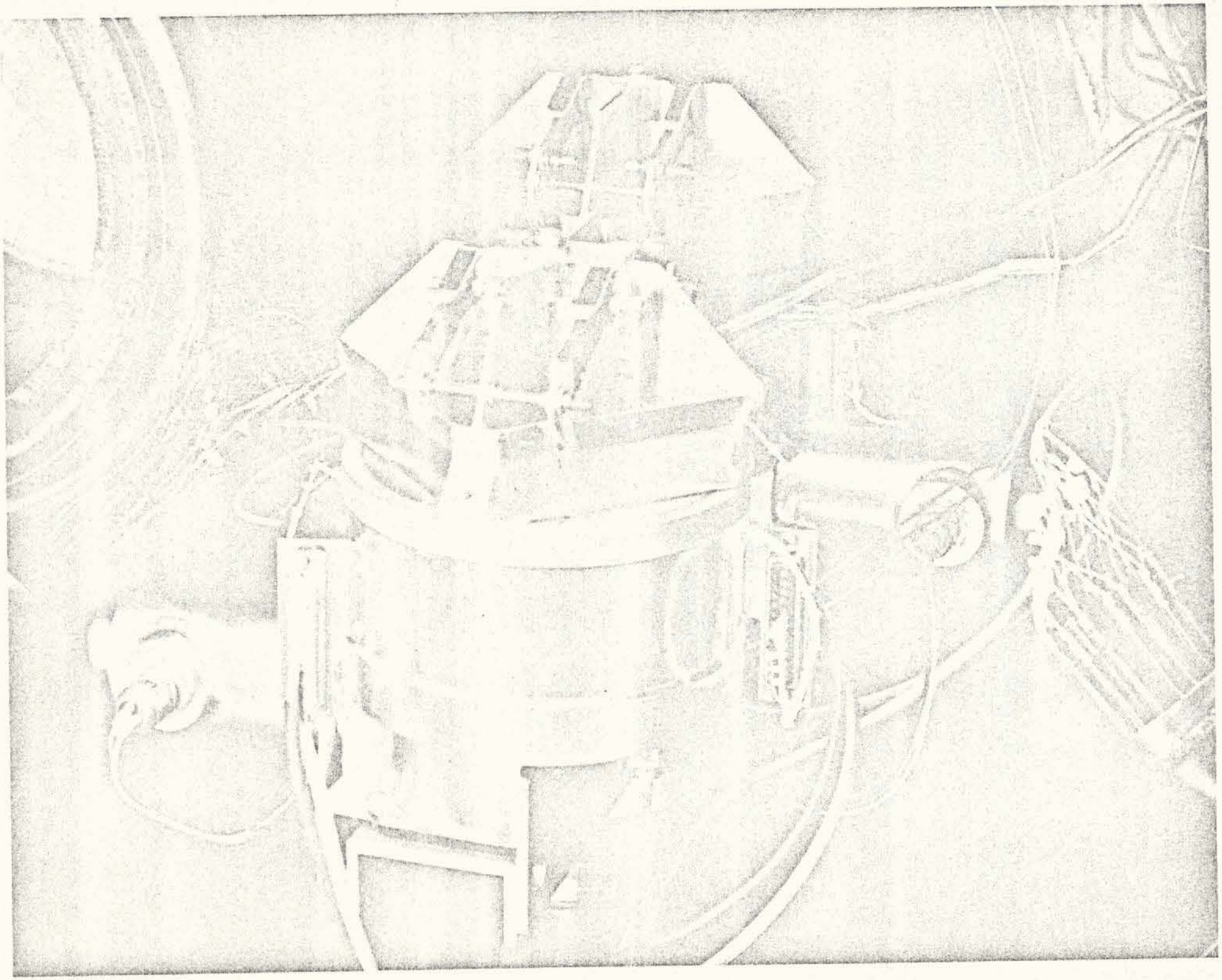

Figure 8. Friction Experiment Modules

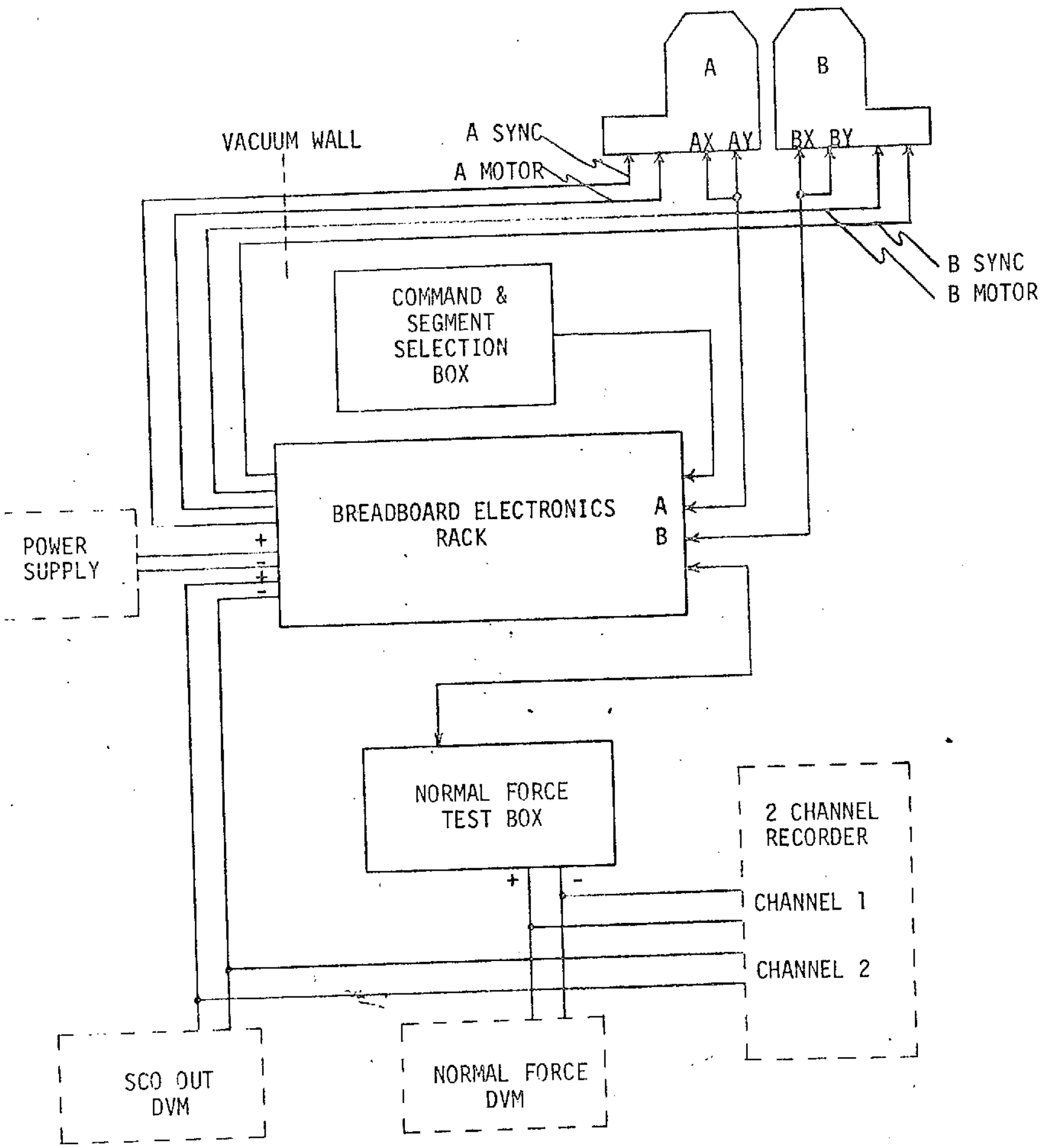

Figure 9. Interconnect Diagram

- Experiment Module

Each experiment module provides the mechanical structure to test eight specimen pairs. A self-contained dc drive motor and cam follower simultaneously drives eight moving specimens, which are individually mounted on the end of the compound flexure arms, across the faces of eight fixed specimens in an oscillating motion. Individual strain gage sensors for each test pair allow measuring a real time analog force signal of both the drag and normal forces. Initial normal forces are set by adjustment of the individual moving sample holders at the end of their flexure arm. Adjustment of the fixed specimen alignment with respect to the moving arm is provided by adjustment nuts at the outboard edge of the fixed specimen support webs.

- Breadboard Electronics Rack

The breadboard electronics rack provides the basic power distribution, control, instrumentation and data processing allowing exercise of the experiment modules. Upon initiation by the Command and Segment Selector Box, these electronics automatically perform predetermined functions using self-contained logic circuits. The signal output is presented in a single channel format containing sequentially commutated information.

- Command and Segment Selection Box

This unit provides for the exercise of the experiment electronics rack with two functions:

a. Command switches allowing initiation of six distinct responses.
b. Self-contained clocks and an external logic inhibition permitting entering and stopping at any pre-selected data segment.

4. ION PUMPED VACUUM FACILITY

The test facility employed in this study was chosen as representative of ion pumped ultrahigh vacuum systems routinely found throughout aerospace organizations. In particular, a room temperature chamber wall provided the major view factor to the experimental apparatus and test surfaces. The facility and the test hardware is shown in Figure 10. The facility consists of a double ended horizontal test chamber 18" dia. X 30" length. The pumping system consists of a 400ℓ/sec ion pump and a titanium sublimation pump (TSP). Roughing the chamber from ambient pressure is accomplished by three sorption pumps. A sorption pump contains an extended surface, porous structure which is cooled to liquid nitrogen temperature to condense the gas. These pumps are periodically rejuvenated by bakeout at elevated temperature. As can be seen in Figure 10, numerous flanges on the test chamber permit the mounting of instrumentation and electrical and mechanical feedthroughs. This facility has been operated empty to less than 10^{-11} torr.

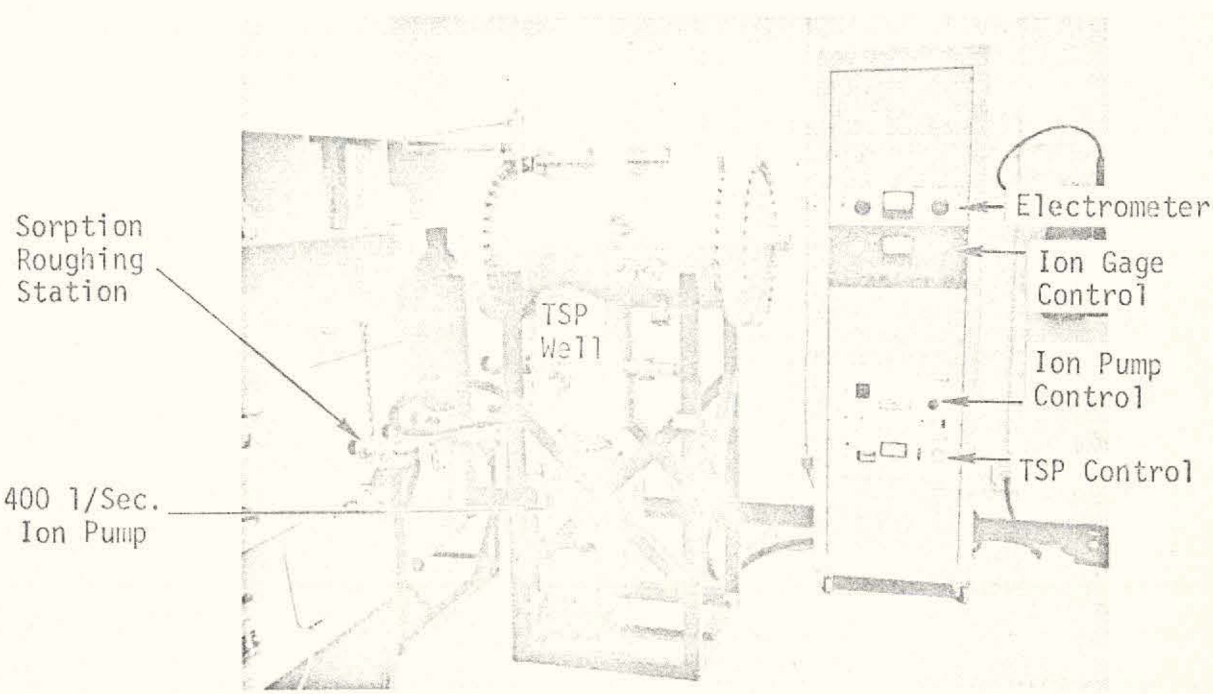

Figure 10
Ion Pumped Friction Test Facility

Throughout the test series the TSP was operated on a programmed basis with continuous cooling of the TSP well surfaces with liquid nitrogen.

Total pressure measurements were made with a nude hot cathode gage of the Bayert-Alpert type mounted in the chamber. No bakeout or other active cleaning methods were used on the chamber or test elements prior to the friction test. Similarly, no active means were employed in any of the previous friction tests.

5. TEST MATERIALS

The primary criteria applied in the selection of the test material couples for the ERS 20 flight test was to provide a cross section of material combinations whose friction might be responsive to variations in the test environment. With limited knowledge of the microfrictional processes for any specific materials, four general classes were considered. The four classes are:

I. Metals and alloys
II. Thin film lubricants
III. Inorganic compounds
IV. Polymers

Table I lists the specific materials selected for test on ERS 20. Also shown in Table I is a list of the materials developed for the ERS 19 flight test which aborted in launch. An extensive solicitation program of test materials was undertaken in developing both lists including reviews with numerous industrial and government organizations which have active friction programs underway. Table II groups the test material categories.

Each material sample used in this program was obtained from a single common stock and batch processed to minimize the effects of materials differences. Rider materials were 1/8" diameter balls crimped in the aluminum flexure arm holders. The fixed specimen was a rectangular flat nominally 1/2 X 1-5/8" x 1/16". Where platings or transfer lubricant films were used, the applicable substrate flat material is indicated on Table I.

Table I

(AFRPL FRICTION TEST MATERIALS)

FRICTION TEST MATERIALS - ERS 20

category*(20)	rider		flat
A	tungsten carbide (WC)	x	tungsten carbide (WC)
B	440C S.S.	x	tungsten carbide (WC)
C	tungsten carbide	x	aluminum oxide (bulk Al_2O_3)
H	tungsten carbide (WC)	x	gold plate (Au/52100)
E	440C S.S.	x	boron nitride (BN)
B	cobalt (Co)	x	tungsten carbide (WC)
D	440C S.S.	x	17-4 PH S.S.
G	440C S.S.	x	burnished tungsten diselenide (WSe_2/17-4PH)
H	cobalt (Co)	x	silver plate (Ag/17-4PH)
D	cobalt (Co)	x	cobalt (Co)
D	cobalt (Co)	x	beryllium (Be)
D	aluminum (Al)	x	beryllium (Be)
F	440C S.S.	x	15% glass filled teflon (PTFE)
F	440C S.S.	x	polyimide (Vespel SP21)
G	440C S.S.	x	burnished natural molybdenum disulfide (MoS_2/17-4PH)
G	440C S.S.	x	burnished synthetic molybdenum disulfide (MoS_2/17-4PH)

FRICTION TEST MATERIALS - ERS 19

category*(19)	rider		flat
D	titanium (5-2.5 Sn)	x	titanium (5-2.5 Sn)
G	440C S.S.	x	double deposited molybdenum disulfide (MoS_2/52100)
D	phospher bronze	x	chrome electrolized 17-4-CRES
H	repeat (Same as ERS 20)		
D	440C S.S.	x	440C S.S.
I	440C S.S.	x	MoS_2 filled polyphenylene
I	440C S.S.	x	MoS_2 filled tantalum (AFSL 15)
G	repeat (Same as ERS 20)		
I	440C S.S.	x	MoS_2 filled teflon (Duroid 5813)
D	repeat (Same as ERS 20)		
G	440C S.S.	x	burnished MoS_2/sulfided 52100
G	440C S.S.	x	polyimide bonded MoS_2/440C
F	repeat (Same as ERS 20)		
F	repeat (Same as ERS 20)		
G	repeat (Same as ERS 20)		
J	P5 carbon	x	sprayed Al_2O_3/52100

*See Table V for category indentification and comparisons

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Table II

AFRPL FRICTION MATERIALS CATEGORY SUMMARY

	Category	General Class	Number of Test Combinations Employed	
			ERS 20	ERS 19
(A)	Carbide X Carbide	III	1	0
(B)	Metal X Carbide	III	2	0
(C)	Carbide X Oxide	III	1	0
(D)	Metal X Metal	I	4	4
(E)	Metal X Nitride	III	1	0
(F)	Metal X Polymer	IV	2	2
(G)	Metal X Lamellar Film	II	3	5
(H)	Metal X Soft Metal Film	II	2	1
(I)	Metal X Composite Lubricant	II,III,IV	0	3
(J)	Metal X Oxide	III	0	1
	Total Sample Combination		16	16
	Total Lubricants		7	11
	Total Unlubricated		9	5

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III
PERFORMANCE OF EXPERIMENTS

1. GENERAL

This section describes the friction test profile utilized in the extended ion pumped vacuum test. Since a comparison is made of these results to previous orbital results, this section also summarizes the orbital test. These descriptions serve as a basis for the data presentations and result discussions contained in the following sections. The orbital, molecular sink, and ion vacuum tests exercised the experiments with identical run profiles. Included were both intermittent and continuous sliding phases. This allowed investigation of environmental and time dependent parameters in addition to studying the effects of cumulative sliding. A special test profile was used in performing the extended ion vacuum test.

For the three previous primary tests the materials on Module A were run to 66 meters of sliding and those on Module B to 120 meters. The duration of the orbital test was fourteen months. By contrast, ten days of vacuum exposure each were used for performing the molecular sink test and ion pumped vacuum test. For the modified ion vacuum test both modules were operated through 120 meters over a ten-day test period. The extended ion pumped test operated Module A in excess of 1500 meters and Module B to 5600 meters.

2. ORBITAL TEST

The orbital test phase was initiated in April of 1967 with the successful launch of ERS 20 (OV5-3) from the ETR aboard a Titan III launch vehicle. The orbit achieved was that nominally planned of 4600 x 60,000 nautical miles. The friction test was initiated 48 hours after spacecraft injection. Orbital data was taken by various STADAN tracking stations under real time control of STADAN Space Physics at Goddard Space Flight Center. Operational limits of the spacecraft dictated that the friction data be acquired at slant ranges of 50,000 km or less between the command station and the spacecraft. The spacecraft/experiment operations were essentially nominal throughout the entire orbital test. Included in the orbital test were both intermittent and continuous run profiles. The initial orbital test plan called for approximately six months of test data. This was later modified to extend the test past twelve months of cumulative space exposure and included an extended passive dwell period and continuous run phases. Friction data was obtained throughout the orbital test for fifteen of sixteen material combinations. As indicated by the telemetered data, the shear pin for the 440C x 17-4 PH stainless steel combination appears to have released after very little sliding.

3. EXTENDED ION PUMPED VACUUM TEST

The ground test friction experiment and electronics were integrated during October 1970 into a TRW Systems Ion Pumped Vacuum Facility. New material specimens from the samples described in Section III were installed. All couples were the same as in the previous test combinations except A7, which tested 440C x AFSL-15 a composite lubricant of MoS_2 in tantalum.

The experiment modules were mounted in the vacuum chamber as shown in Figure 11. A channel section provided the structural element between the chamber wall and the two modules.

The operational status of the friction experiment modules was such that all sixteen material combinations could be tested. After a pretest checkout following integration, the vacuum test phase was initiated and the predetermined 120 meter experiment run profile for the modified ion pumped test implemented. Table III provides the experiment operational summary for the extended ion pumped vacuum test which was a continuation of the previous sliding history.

TABLE III
EXTENDED ION VACUUM PERFORMANCE SUMMARY

DATE	MODULE	DATA RUN	LAPSED TIME HOURS	LAPSED TIME MINUTES
APRIL 21, 1971	A	11		00
APRIL 26, 1971	A	12		12
		13		24
		14		19
		15		24
		16		30
		17		18
		18		30
		19		30
		20		30
		21		30
APRIL 27, 1971	A	22		60
		23		42
		24		32
		25		48
		26		48
		27		54
		28		60
		29		72
		30		66

TABLE III (cont'd)

DATE	MODULE	DATA RUN	LAPSED TIME	
			HOURS	MINUTES
[illegible]IL 28, 1971	A	31		78
		32		72
		33		96
		34		84
		35		108
[illegible]RIL 29, 1971	A	36	2	
		37	2	
		38*	2	
[illegible]PRIL 30, 1971	A	39	2	12
		40	2	18
		41**	2	54
[illegible]AY 17, 1971	A	42	3	6
		43	3	
		44***	3	30

* Ran for 1 hour and 41 minutes. Motor current increasing then stopped. On again to complete run.

** Motor stopped at 5 min. early. Drawing 450 mils. Power supply set to limit at 450 mils.

*** Removed from chamber-bellows leak.

TABLE III (cont'd)

DATE	MODULE	DATA RUN	LAPSED TIME	
			HOURS	MINUTES
APRIL 15, 1971	A - B	10a		
APRIL 16, 1971	B	11		00
		12		12
		13		24
		14		19
		15		24
		16		30
		17		18
		18		30
		19		30
		20		30
		21		30
APRIL 19, 1971	B	22		60
		23		42
		24		32
		25		48
		26		48
		27		54
		28		60
		29		72
		30		66
APRIL 20, 1971	B	31		78
		32		72
		33		96
		34		84
		35		108
APRIL 21, 1971	B	36		120
MAY 3, 1971	B	37	2	
		38	2	

TABLE III (cont'd)

.ll	MODULE	DATA RUN	LAPSED TIME HOURS	MINUTES
., 1971	B	39	2	12
., 1971	B	40	2	18
., 1971	B	41	2	54
		42	3	6
7, 1971	B	43	3	
		44	3	30
10, 1971	B	45*	4	
E 28, 1971	B	46	3	30
Y 2, 1971	B	47**	4	
		48	4	
Y 6, 1971	B	49	5	
		50	5	
Y 7, 1971	B	51	7	
		52	5	
Y 8, 1971	B	53	7	
		54	7	
Y 9, 1971	B	55***	9	

*Module B motor stopped. Bellows leak.

**Drive shaft broke.

***The ball bearing on the drive mechanism wore out.

The method of test differed somewhat from all previous studies in that a logarithmic sample rate of data acquisition was used. Between scheduled data taking events the experiment was run continuously by-passing the normal integral clocks and counters of the ground test electronics. During the actual data acquisition the complete ground test electronics package was used. Figure 12 illustrates the data acquisition frequency used versus accumulated sliding.

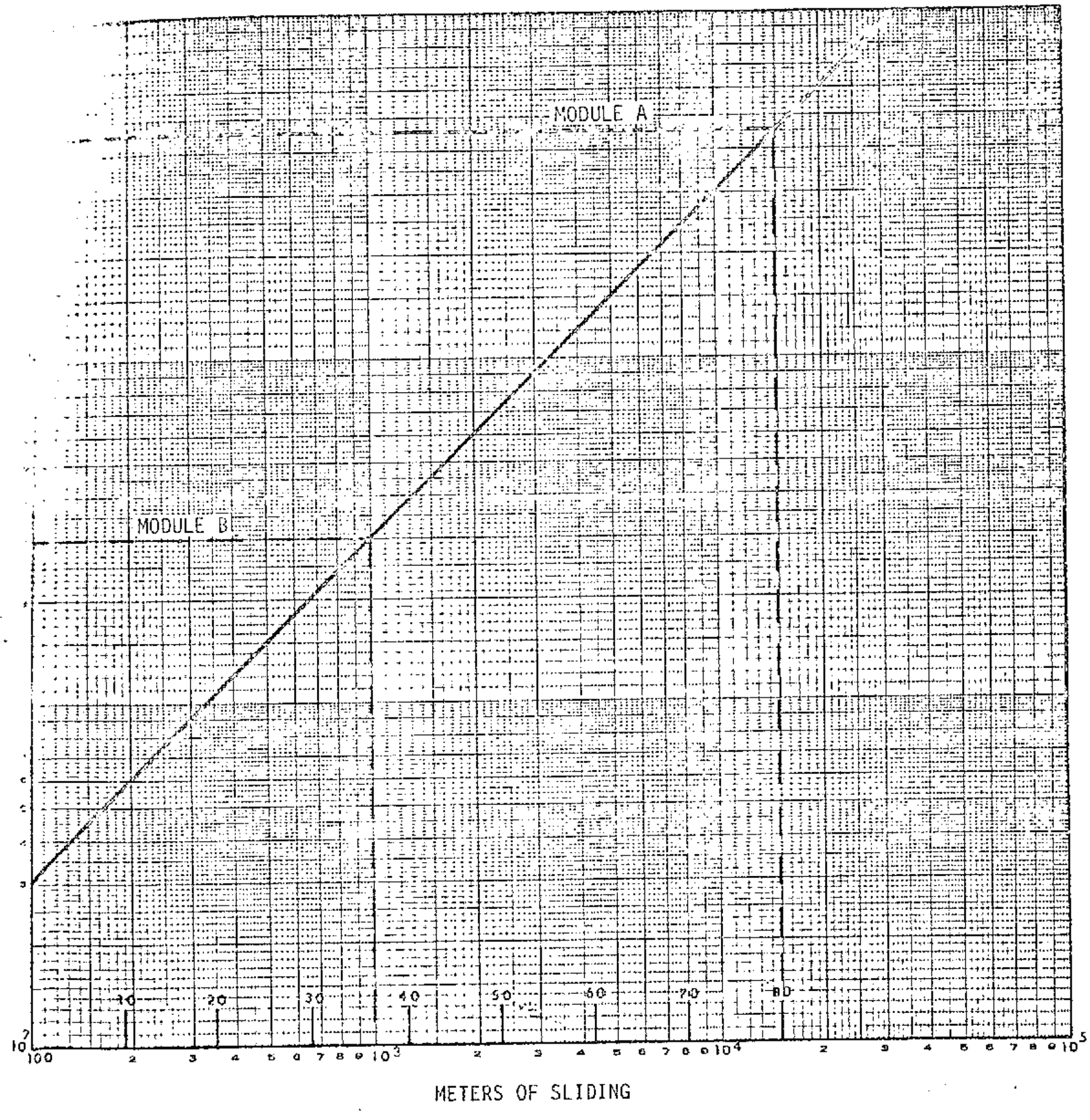
Original plans called for operation of Module B to 1000 meters of sliding and Module A through 15,000. Recognizing the possibility of mechanical wear out of the test hardware, pre-planned alternatives allowed reversing the role of which module would be used for the greater extended sliding. Furthermore, should mechanical reasons terminate both modules in test, the necessary repair was to be effected and the test continued to 5000 rather than 15,000 meters.

During performance of the test, all options were exercised. Initially Module B was exercised through 1000 meters of sliding in early April. Subsequently, the longer Module A test was started and proceeded through about 1500 meters. At 1500 meters an anomalous drive motor current and subsequent failure to run was encountered. Rather than break vacuum, Module B was placed into extended test wherein at nearly the same total sliding ∿1500 meters an analogous behavior was observed.

Since both modules were inoperative it was necessary to terminate the test and remove the modules from the chamber for inspection and repair. Following a brief examination, it was ascertained the motor failures were the result of a loss of vacuum seal due to a fatigue failure of the main bellows. This failure is shown in Figure 13. Analysis of the total number of stress-reversal (∿35,000) cycles each module had encountered and the appropriate bellows life expectancy formulas, showed the failures fell within the predicted values.

New bellows assemblies were ordered with a material substitution providing for greater cycle lifetimes incorporated. Because of the prior vacuum

FIGURE 12. Estimated Experiment Run Time vs. Sliding Distance



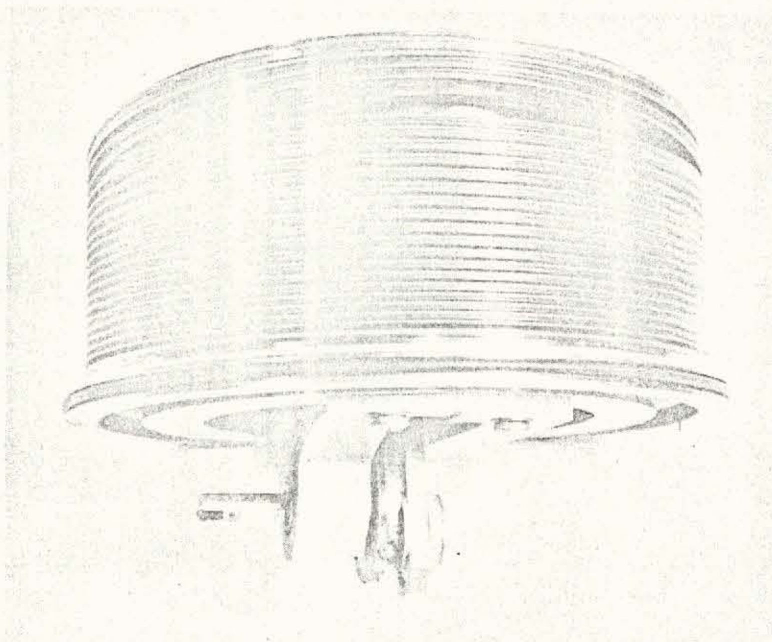


FIGURE 13. Fatigued Bellows

operation effects on the drive motor assemblies, these were felt unreliable and an available spare motor substituted.

After six weeks delay necessary for bellows delivery and module reassembly, Module B was placed back into test. However, a series of other mechanical failures necessitated two additional disassembly and refurbishment operations. Fortunately, residual hardware in the form of bearings involved in the original manufacture were available. Damaged flexure arm assemblies were replaced by cannibalized elements taken from Module A.

IV
RESULTS SUMMARY

1. GENERAL

Extended sliding friction data for sixteen material combinations was obtained under ion pumped vacuum conditions. Compared with the results of previous tests conducted in oil pumped ultrahigh vacuum, controlled environment degraded vacuum and in satellite orbital test conditions, the friction behavior is found to generally match the orbital results. Whereas previous studies showed that the microfrictional process between different material combinations is sensitive to different aspects of a test environment, this study showed that continued sliding of a given test pair did not measurably alter previous findings except as wear out was noted.

Specific results for each material combination are discussed in the following section. Appendix A presents individual coefficient of friction graphs for each material combination for both the orbital and the extended ion pumped vacuum tests. Since the extended friction data is a continuation of the previous modified ion pumped test, the curves include this data as the first 120 meters.

Appendices B, C & D provide the graphical results for the oil pumped, molecular sink, and ion pumped friction tests respectively.

2. SUMMARY

Summary results are as follows:

1. In two instances (Co X Be and Co X WC) the maximum friction force noted in the extended friction test did not achieve the values observed during the orbital test. An earlier ion pumped test of Co X Be (AFRPL TR-70-120) did show excellent agreement. In the case of Co X WC the current study shows a frictional behavior comparable to the previous ion pumped behavior. The lower frictional force for these two couples was noted in the prior modified ion pumped test with extended sliding producing no clarification of the observation.

frictional behavior for all couples throughout the extended ding tests generally agrees with shorter sliding distance generated in previous tests. Wear out of selected binations was noted.

nterruption of the vacuum conditions permitted evaluation of he alteration (if any) and rate of recovery on the frictional forces. Several couples exhibited transitory reduction in friction following air exposure which returned to the vacuum value upon continued sliding in vacuum.

4. No evidence of static friction in the classical sense was evidenced in the data records using an intermittent mechanical test and an oscillating slide profile which routinely passed through zero velocity.

5. Passive mechanical history (non-sliding) was found to produce a measurable increase in running friction on the thin film lubricants tested. Passive dwell had little, if any, relative effect on the other material combinations.

6. Accumulated mechanical sliding (mileage) was found to be the dominant factor in controlling the development of friction in space, the molecular sink and ion pumped vacuum and modified in vacuum except as previously noted.

7. Observable mechanical sliding incubation (an initial amount of sliding during which the friction increases) was found for several of the unlubricated material combinations.

8. In the orbital test program the greatest discrepancy between frictional behavior in oil pumped ultrahigh vacuum and space was found for unlubricated metal systems. Such differences were not noted in either the molecular sink or the ion pumped tests.

9. No universal conclusions from these tests regarding the influence of hardness, solubility, or crystal structure can be made. Generally those materials having a high shear strength exhibit high coefficients of boundary layer friction. It is suggested that for unlubricated combinations, true contact area growth may be a controlling factor in the specific friction developed between a test configuration of a ball on a flat.

10. Based upon the differences found in previous studies between data from a room temperature wall/oil pumped ultrahigh vacuum and orbital conditions, this type of simulated space environment may be unacceptable for determining force limiting frictional processes for certain material combinations.

11. Agreement of friction of some material pairs in all the conditions studied in the previous programs and in this study indicates that less sophisticated and expensive testing can be used in evaluating some materials in hardware designs.

12. No evidence of friction dependence on orbital altitude was found.

13. Summarized on the following page are typical coefficient of friction values for each test combination. Included in this summary are data taken in an oil pumped ultrahigh vacuum. Comparison of this with the orbital data showed general agreement between seven combinations and disagreement of eight combinations; no definitive tests of one combination occurred.

    By contrast, a comparison of molecular sink test data shows twelve of thirteen combinations agree. The early wear out of synthetic MoS_2 in the flight test may have been the result of a non-typical sample. For three material combinations no direct comparisons could be made. The lack of orbital data

FIGURE 14. Extended Ion Pumped Characterization

Comparison of Orbital, Post Launch UHV, Molecular Sink and Ion Pumped Results

Experiment Designation	Material*	u_k Flight†	u_k Post Launch†	Disagree	Agree	u_k Mol. Sink†	Disagree	Agree	u_k Ion†	Disagree	Agree	Ext/Mod. u_k Ion	Disagree	Agree
A1	440C x BN	0.35 - 0.85	0.2 - 0.4	X		0.4 - 0.8		X	0.4 - 0.8		X	0.4 - 0.9		X
A2	440C x Syn. MoS_2	0.1 wear out	0.04	X		0.03	X		0.04	X		0.04 wearout	X	
A3	440C x WC	0.85	0.65	X		0.85		X	0.8		X	0.8		X
A4	440C x 17-4 PH	0.1 shear pin	0.9 - 1.1	no test		1.2 - 1.6	no test		1.0	no test		1.4	no test	
A5	Co x Be	1.6 - 2.2	0.45	X		1.5 - 2.0		X	1.6 - 2.0		X	1.0	X	
A6	Co x Co	0.5	0.4		X	0.4		X	0.4		X	0.5		X
A7	WC x Au	0.15 - 0.3	0.15 - 0.25		X	0.15 - 0.3		X	0.?		X	440CxAFSL-15(0.15)diff. matl pair		
A8	440C x Polyimide	0.2 - 0.3	0.27		X	0.26		X	0.2 - 0.3		X	0.2 - 0.3		X
B1	440C x WSe_2	0.04	0.05		X	0.04		X	.04		X	.05 wearout		X
B2	Co x Ag	0.2 - 0.4	0.2 - 0.4		X	0.2 - 0.4		X	0.3-0.4 wear out	X		0.5-1.0 wearout	X	
B3	WC x WC	0.75 - 1.2	0.55	X		no data	no test		0.85 - 1.3		X	0.8 - 1.2		X
B4	WC x Al_2O_3	0.3 - 0.6	0.5		X	0.4 - 0.6		X	0.45 - C.6		X	0.5 - 0.6		X
B5	Al x Be	0.25 - 0.9	0.35 - 0.65	X**		0.3 - 0.55	X**		0.4 - 0.65	X**		0.3 - 0.6	X**	
B6	Co x WC	0.3 - 1.6	0.65	X		no data	no test		0.45 - 1.3		X	0.4 - 0.8	X	
B7	440C x PTFE	0.2	0.1	X		0.2		X	0.2		X	0.18		X
B8	440C x Nat. MoS_2	0.03 wear out	0.04		X	0.03 wear out		X	0.04		X	0.03 wearout		X

materials section for description.

coefficients of friction, u_k, represent typical data obtained in each set of tests.

ated to intermittent run affects noted only in orbital test

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for one of these was due to the release of a shear pin during the flight test. Two combinations were not tested in the molecular sink tests because of inoperative strain gages.

The ion pumped friction tests show good agreement between 14 of the 16 materials pairs. The lack of correlation in the synthetic MoS_2 test is attributable to the lack of significant test data in the flight test. The result is comparable to previous ground tests suggesting an abnormality in the flight test sample. The early wear out of the silver coated sample in ion pumped tests did not occur in any of the previous test series. Prior to wear out, the friction value appeared nominal.

V
DISCUSSION OF RESULTS

1. GENERAL

The individual behavior of the friction test couples is discussed in this section. General features have been summarized in the Results Summary. A graphical comparison of the frictional behavior for fifteen of the material couples tested in this study with previous test results can be made by examination of the graphs in Appendix A with Appendices B, C & D. Each couple can also be examined for the influences of the test profiles and deliberately controlled environmental parameters.

Appendices B, C & D present graphs of the data obtained in the three previous ground tests: oil pumped, molecular sink and ion pumped vacuums. Details of these tests are contained in References 1, 2 & 6.

All data is shown as a coefficient of friction. The coefficient of friction is defined as the measured sliding force divided by the applied normal force between the translating surfaces.

$$\text{Kinetic coefficient of friction} \quad \mu_k = \frac{F_{sliding}}{F_{normal}} = \frac{F_S}{F_N}$$

While the data is presented as a coefficient of friction, the reader should be cautioned, these reported values of friction for the test materials are only representative of the loads and geometries tested here. Other geometries and loads may exhibit significantly different frictional behavior.

2. SPECIFIC MATERIALS BEHAVIOR

The following specific discussions of each material couple have been developed by examination of the pertinent graphs of Appendices A, B, C & D.

a. A1 - 440C x BN

(1) The extended, modified ion vacuum, ion vacuum, molecular sink and orbital tests demonstrate the same average sliding friction.

(2) All tests show a considerable variation in friction from run to run.

(3) None of the tests suggests intermittent sliding produces a systematic change in the frictional behavior.

(4) The friction behavior of this pair shows no apparent change by exposure to the modified ion vacuum conditions.

b. A2 - 440C x Synthetic MoS_2.

(1) The modified ion vacuum results agree with all other ground tests. The extended ground test demonstrates a wear out as noted in the orbital test.

(2) All tests show that non-sliding produces a higher friction which is not noted with continuous sliding.

(3) The friction behavior of this pair shows no sensitivity to any of the modified ion vacuum conditions.

c. A3 - 440C x WC

(1) The extended ion vacuum coefficient of friction agrees well with previous ion vacuum, molecular sink and orbital tests.

(2) All tests show a strong mechanical sliding incubation of about ten meters prior to reaching the equilibrium friction behavior.

(3) There is no evidence of a friction dependence with intermittent sliding conditions in any of the tests.

(4) The friction behavior of this pair was uneffected by any of the modified ion vacuum environments.

d. A4 - 440C x 17-4PH

(1) The modified ion vacuum coefficient of friction agrees well with that of the molecular sink and ion vacuum

tests. A shear pin release of this couple in orbital test negates any orbital friction comparison.

(2) All tests show strong mechanical sliding incubation up to twenty meters sliding to reach the equilibrium friction behavior.

(3) The friction behavior of this pair was uneffected by any of the modified ion vacuum environments.

(4) No evidence of intermittent sliding effects was found in any of the tests.

(5) A continued rise in friction force with cumulative sliding was noted in the extended ion vacuum test.

e. A5 - Co x Be

(1) The friction behavior of this couple does not agree with that of the orbital, molecular or ion pumped vacuum.

(2) Previous orbital, molecular sink and ion vacuum ground tests show a continuously rising friction. Extensive sliding in the current study provides no clarification as to why the behavior was different.

(3) No evidence of intermittent sliding effects was found in any of the tests.

f. A6 - Co x Co

(1) The extended ion vacuum coefficient of friction agrees well with all previous tests.

(2) In all tests a very minor mechanical sliding incubation was noted.

(3) No evidence of intermittent sliding effects was found in any of the tests.

(4) The friction behavior of this pair was unaffected by any of the modified ion vacuum environments.

g. A7 - 440C x AFSL-15

(1) No evidence of mechanical sliding incubation is noted for this couple.

(2) No alteration in friction with intermittent sliding is found.

(3) No change in friction during modification of the ion pumped vacuum was found.

(4) As this pair was not previously tested, no comparisons are made.

h. A8 - 440C x Vespel SP-21

(1) General agreement of the modified ion vacuum frictional behavior with that for all previous tests is evidenced.

(2) No test shows evidence of any intermittency, dependency or mechanical sliding incubation.

(3) The orbital and ion pumped tests show a decrease in friction under continuous sliding.

(4) Decreases in friction found in the modified ion vacuum tests suggested as being a function of continuous sliding rather than an environmental influence are strongly in evidence with the extended vacuum test.

i. B1 - 440C x WSe_2

(1) The extended ion vacuum results agree with those of the previous ground and orbital tests.

(2) Intermittent sliding consistently results in an initial increase in friction which reduces with continued rubbing.

(3) All tests show a modest increase in the coefficient of friction with accumulated sliding.

(4) The friction behavior of this pair shows no sensitivity to any of the modified ion vacuum conditions.

(5) No significant mechanical incubation is evidenced for this couple.

(6) Wear out occurred during the extended sliding study.

j. B2 - Co x Ag

(1) The extended ion pumped vacuum friction agrees only with the previous ion pumped friction study which also indicated a rapid wearout of the silver. Similar behavior was not noted in previous ground nor the orbital test phase. Wearout in the latter two tests is thought to be related to sample aging.

(2) The modification of an ion vacuum produced a decrease in the friction of this couple with nitrogen, water and oxygen. However, argon, carbon dioxide, and methane additions produced no apparent change. The specific influence noted is likely associated with the formation of nitrides and oxides of silver.

(3) No significant mechanical incubation is evidenced for this couple.

(4) Friction during the extended sliding study was dominated by the substrate materials.

k. B3 - WC x WC

(1) All tests show mechanical incubation of about 5 meters sliding to reach the equilibrium sliding friction.

(2) The typical coefficient of friction in the modified ion pumped vacuum agrees with that of the orbital, mol sink and ion pumped vacuum tests.

(3) No evidence of a friction sensitivity to any of the extended ion pumped vacuum environments was noted.

l. B4 - WC x Al_2O_3

(1) Indication of mechanical incubation was noted in modified ion and orbital tests. No such sliding incubation was found in the mol sink or ion vacuum tests.

(2) The general coefficient of friction of the modified ion vacuum tends to agree with previous orbital and other ground tests.

(3) Water vapor introduction in both the modified ion vacuum and earlier modified oil pumped vacuum produced a decrease in friction.

m. B5 - Al x Be

(1) There is general agreement between the results of the modified ion vacuum, ion vacuum, mol sink and orbital tests.

(2) The orbital test shows an intermittency effect where the friction is highest with following long intermittent dwell periods.

(3) Mechanical incubation appears to be inconsistent from test to test.

(4) A suggested time dependent adhesion was found only in the orbital test.

(5) The modified ion vacuum friction showed no sensitivity to the conditions studied.

n. B6 - Co x WC

(1) There is apparently some effect on limiting the increase in friction with continued sliding in the extended ion vacuum friction when compared to previous orbital and ion pumped test results.

(2) Some evidence of a sliding mechanical incubation is found in all the tests.

(3) No evidence of an intermittent effect upon friction was noted.

(4) No specific alteration of friction due to exposure to a particular modified ion vacuum is noted.

o. B7 - 440C x PTFE Teflon

(1) The extended ion vacuum friction and all previous tests demonstrate the same average friction.

(2) No evidence of intermittent sliding behavior was found in any test.

(3) Slight mechanical incubation was evidenced in the orbital test.

(4) No evidence of a change in the friction with any of the modified ion vacuum environments was found.

n. B8 - 440C x Nat MoS_2

(1) The extended ion vacuum test friction agrees well with previous orbital and simulated space vacuum friction.

(2) Wearout after the same nominal sliding occurred in the orbital and mol sink tests.

(3) Higher friction immediately following intermittent sliding dwells was consistently found in all tests.

(4) No evidence of a friction change with any of the modified ion vacuum conditions was noted.

VI
CONCLUSIONS

The extended ion pumped vacuum friction test shows good agreement with ERS 20 orbital test results generated under contract AF 04(611)-10747, molecular sink results generated under contract F04611-69-C-0080 and ion pumped vacuum data generated under contract F04611-70-C-0029. By contrast, the orbital friction test data did not correlate for about 50% of comparative friction data generated in an oil pumped ultrahigh vacuum. All materials which did not correlate showed considerably higher frictional behavior in the orbital test.

In this test two couples continued to exhibit a lower limiting friction force as earlier noted under the modified ion vacuum conditions, contract 952996. These two couples, Co X Be and Co X WC showed no sensitivity to a particular modifying gas during the previous phase. Rather the development of the ultimate friction force was less than that noted in space vacuum. A similar friction value in ion pumped vacuum was noted for the Co X WC couple. Extended sliding did not resolve the difference noted for either couple between the space and ground test behaviors.

General frictional values measured throughout the extended sliding test confirm the applicability of the frictional characteristics and comparisons established with shorter mechanical testing profiles in the previous vacuum test studies.

Wear out of thin film lubricants was noted. Two couples showed a continuous increase in friction with continued sliding throughout the extended sliding test. All other pairs achieved a fairly constant friction force following some initial sliding under vacuum. The two couples with continuously increasing force apparently continue to modify their contacting surfaces. The rate of such modification is a function of the geometries and normal force loads imposed.

While the friction coefficients between several couples became quite high in no case did any pair evidence gross sticking (coldwelding).

Interruption of the extended sliding vacuum test to repair the experimental units showed either no effect or a rapid recovery to the earlier friction values upon re-establishing sliding in vacuum. These results reinforce the premise that the sliding distance (mechanical history) is the primary factor in establishing the force limiting boundary layer friction.

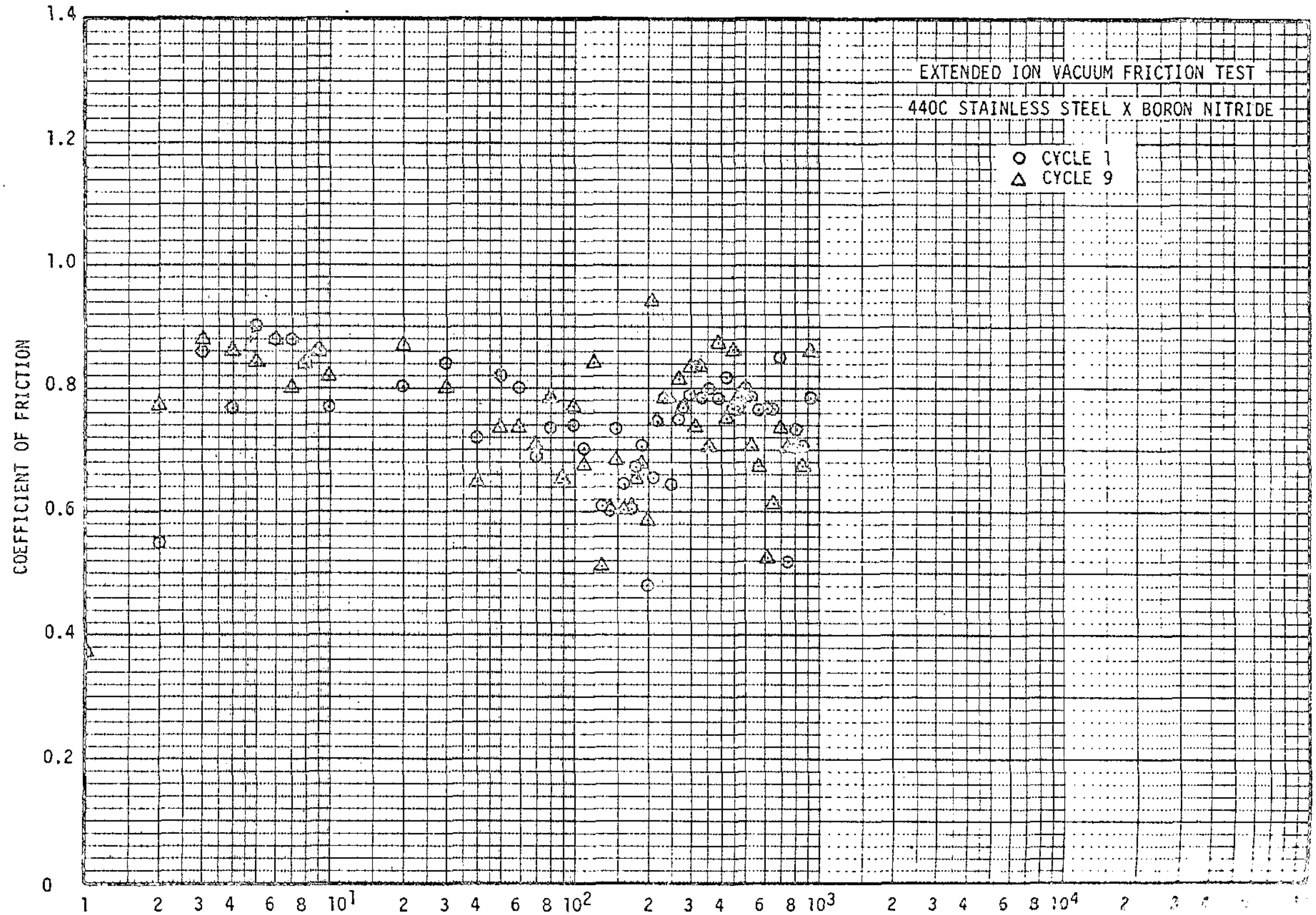
These friction results are not considered inconsistent with clean surface studies and normal force adhesion measurements of metals which show strong sensitivities to minor vacuum environment variations. Rather, this illustrates the strong role micromechanics plays in dominating the shear force development between engineering materials sliding over engineering dimensions.

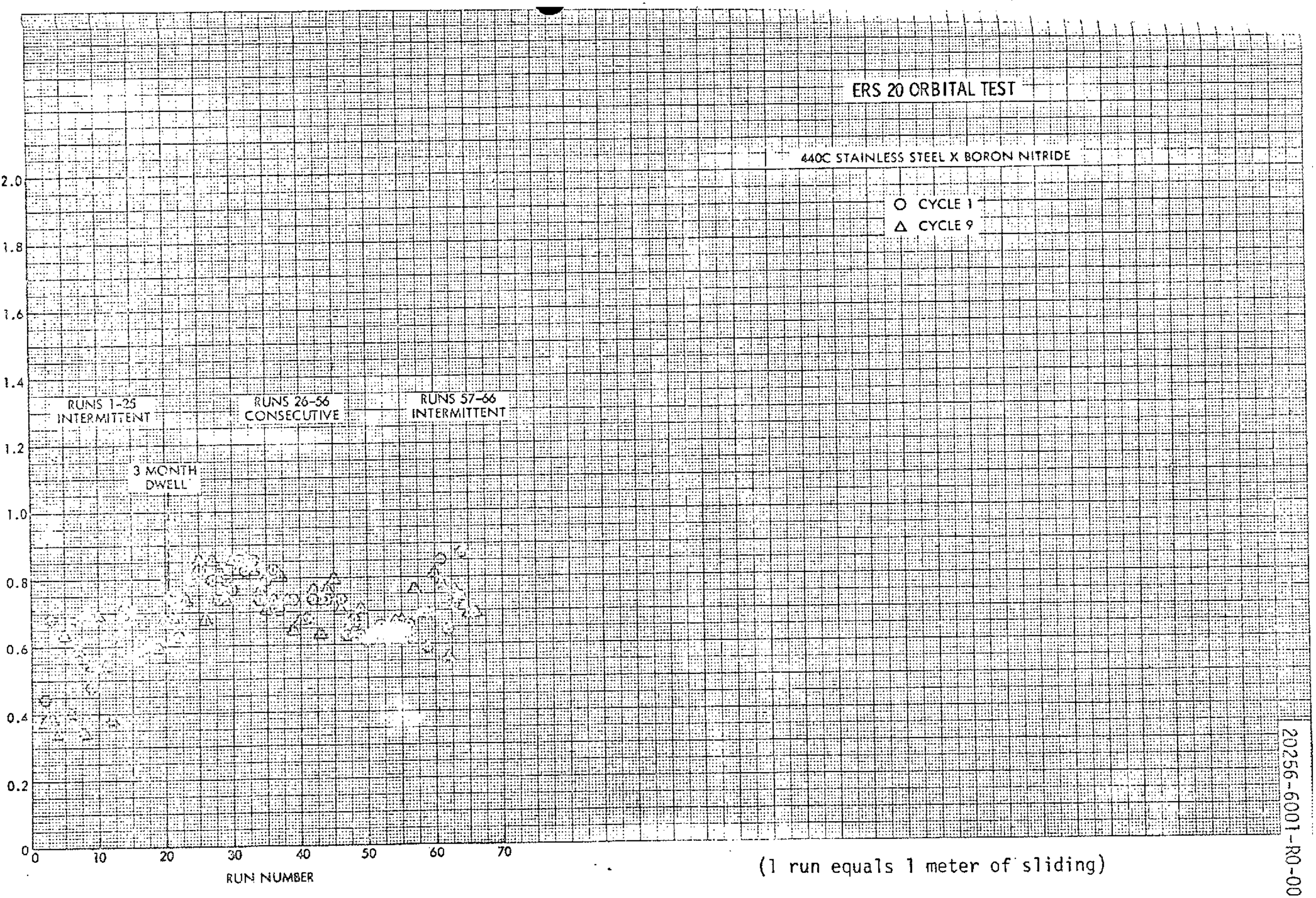
Of prime interest is the general observation that the in-space and both molecular sink, ion pumped friction results were controlled by the mechanical history and appeared independent of the exposure time. Where space mechanisms are receiving additional time dependent contaminant gas loads from space system hardware, no limiting test conditions will apply. The result of space vacuum time independence indicates that meaningful friction material and design evaluations are possible using the mechanical history (mileage) as the primary test control for measuring the limiting forces and assessing potential wear out.

APPENDIX A
EXTENDED ION VACUUM DATA & ORBITAL DATA

This section contains graphical presentations of the friction data for the sixteen material combinations studied in the Modified Ion Pumped Vacuum Facility. Shown on the opposing page is the corresponding orbital friction curve except for A7 which is a new test combination in this study.

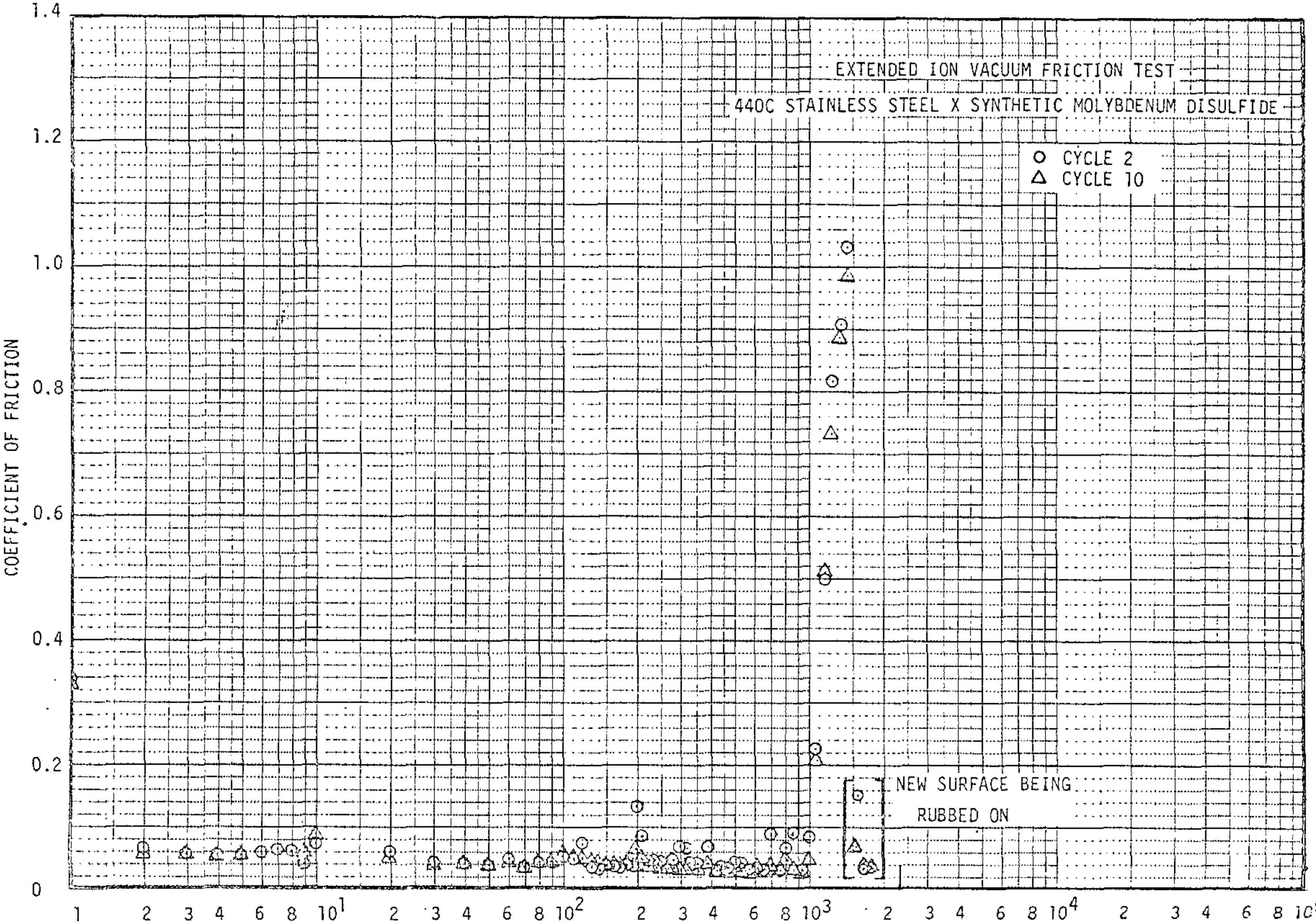
The order of presentation is by designation on the experiment modules A1-8 and B1-8.

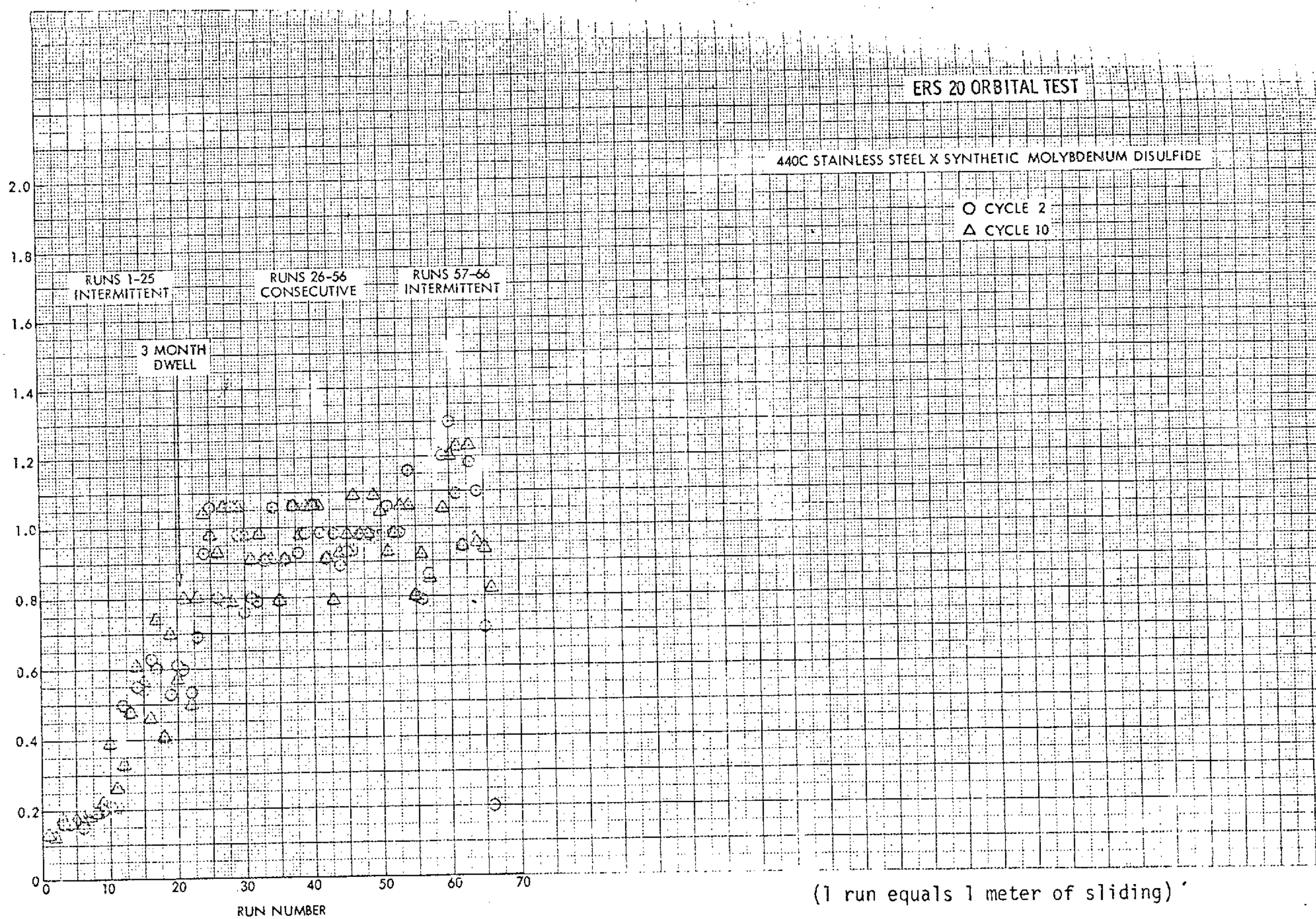

EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X BORON NITRIDE
CYCLE 1
CYCLE 9
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
6
8
10^1
10^2
10^3
10^4



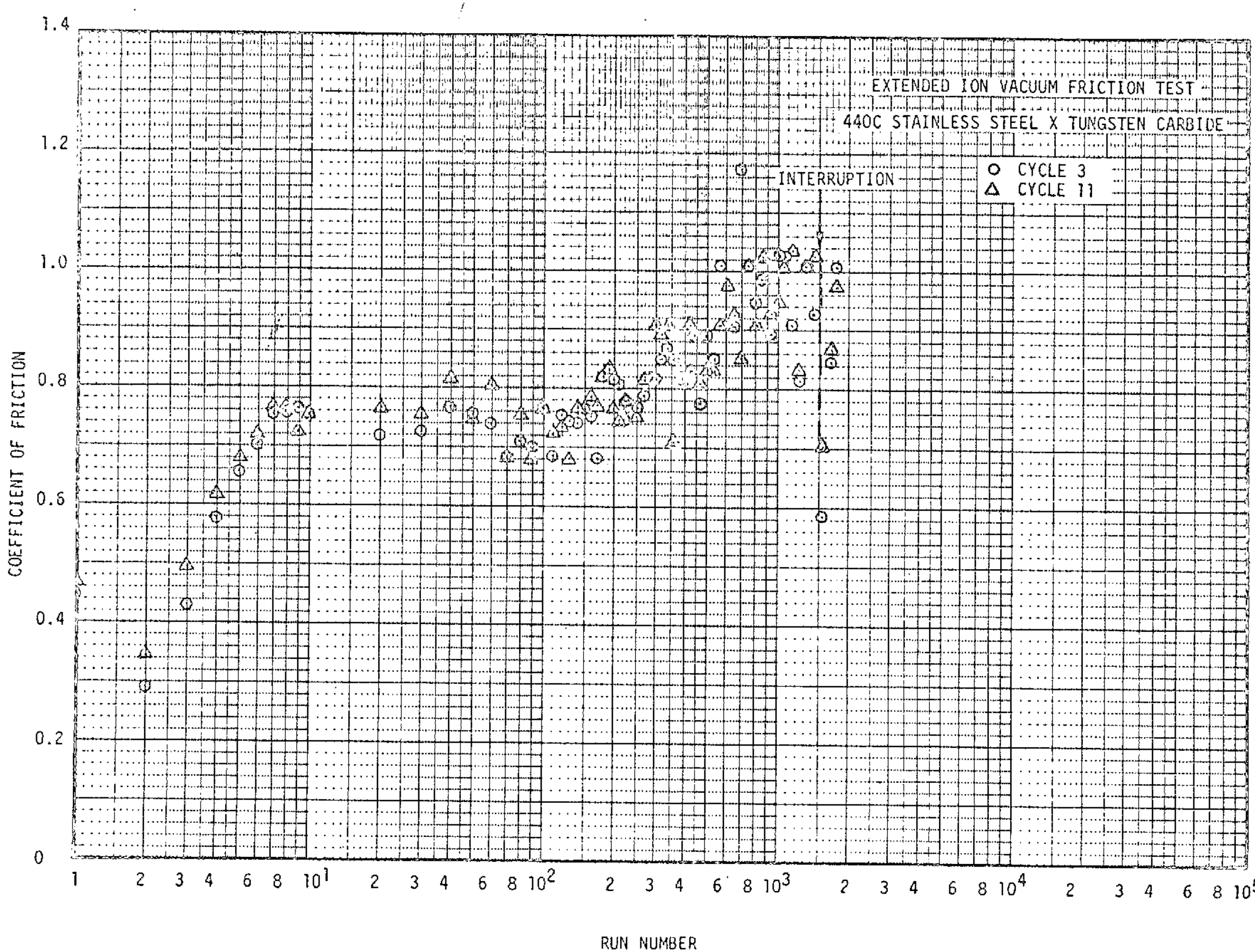
(1 run equals 1 meter of sliding)

51

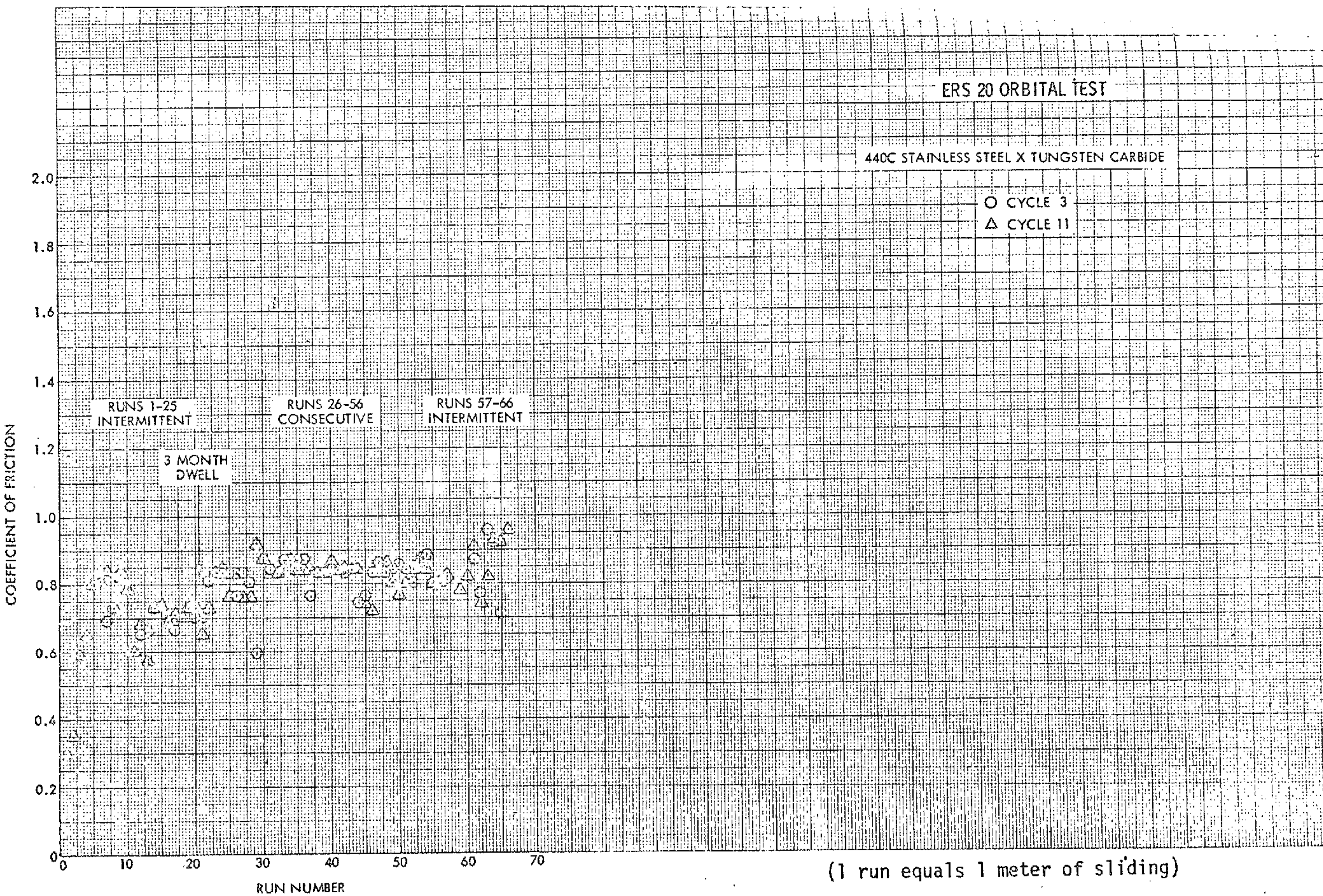

EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X SYNTHETIC MOLYBDENUM DISULFIDE
CYCLE 2
CYCLE 10
NEW SURFACE BEING
RUBBED ON
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1 2 3 4 6 8 10¹ 2 3 4 6 8 10² 2 3 4 6 8 10³ 2 3 4 6 8 10⁴ 2 3 4 6 8 10⁵



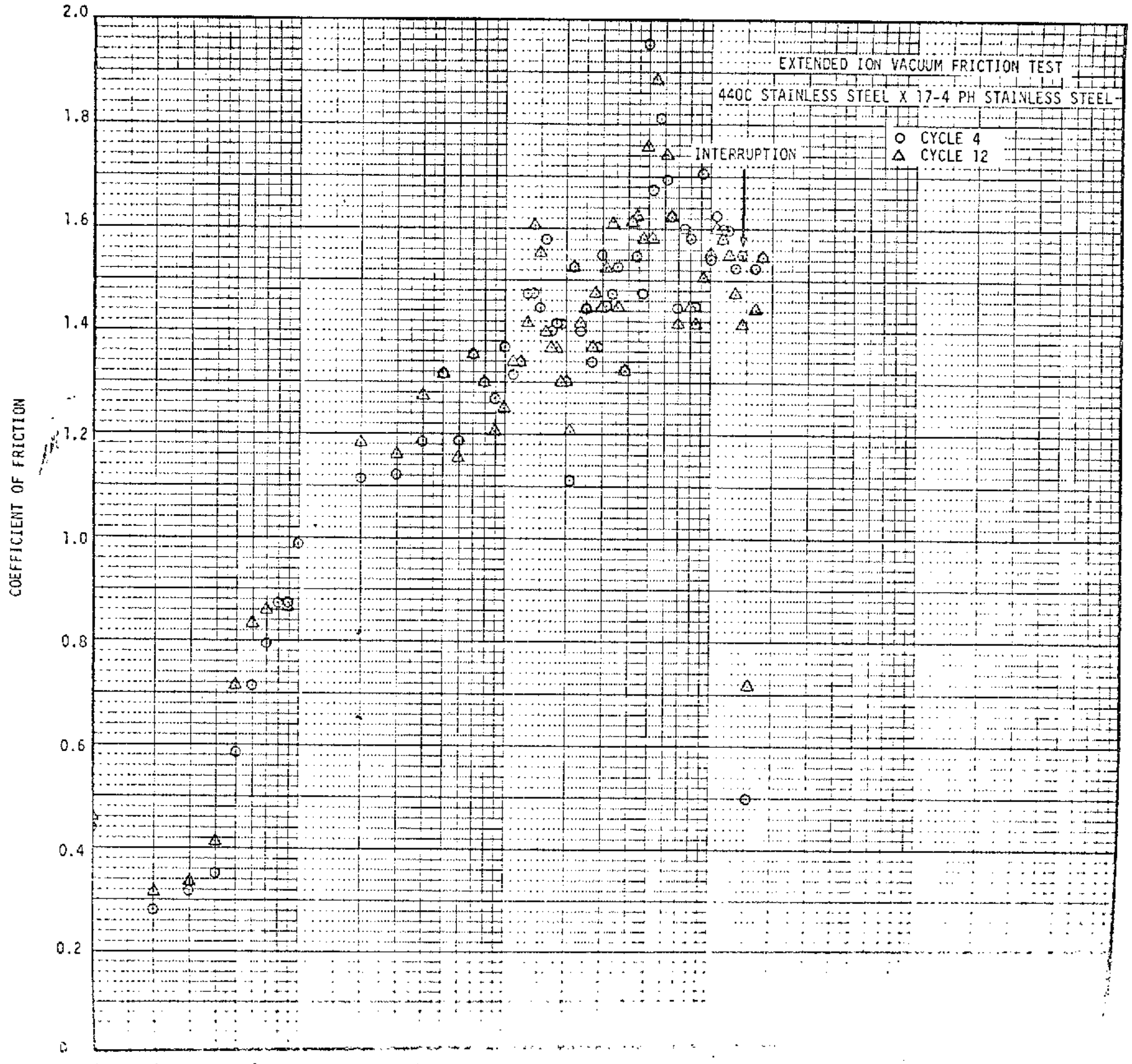
(1 run equals 1 meter of sliding)



EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X TUNGSTEN CARBIDE
INTERRUPTION
CYCLE 3
CYCLE 11
COEFFICIENT OF FRICTION
RUN NUMBER
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 4 6 8 10^5



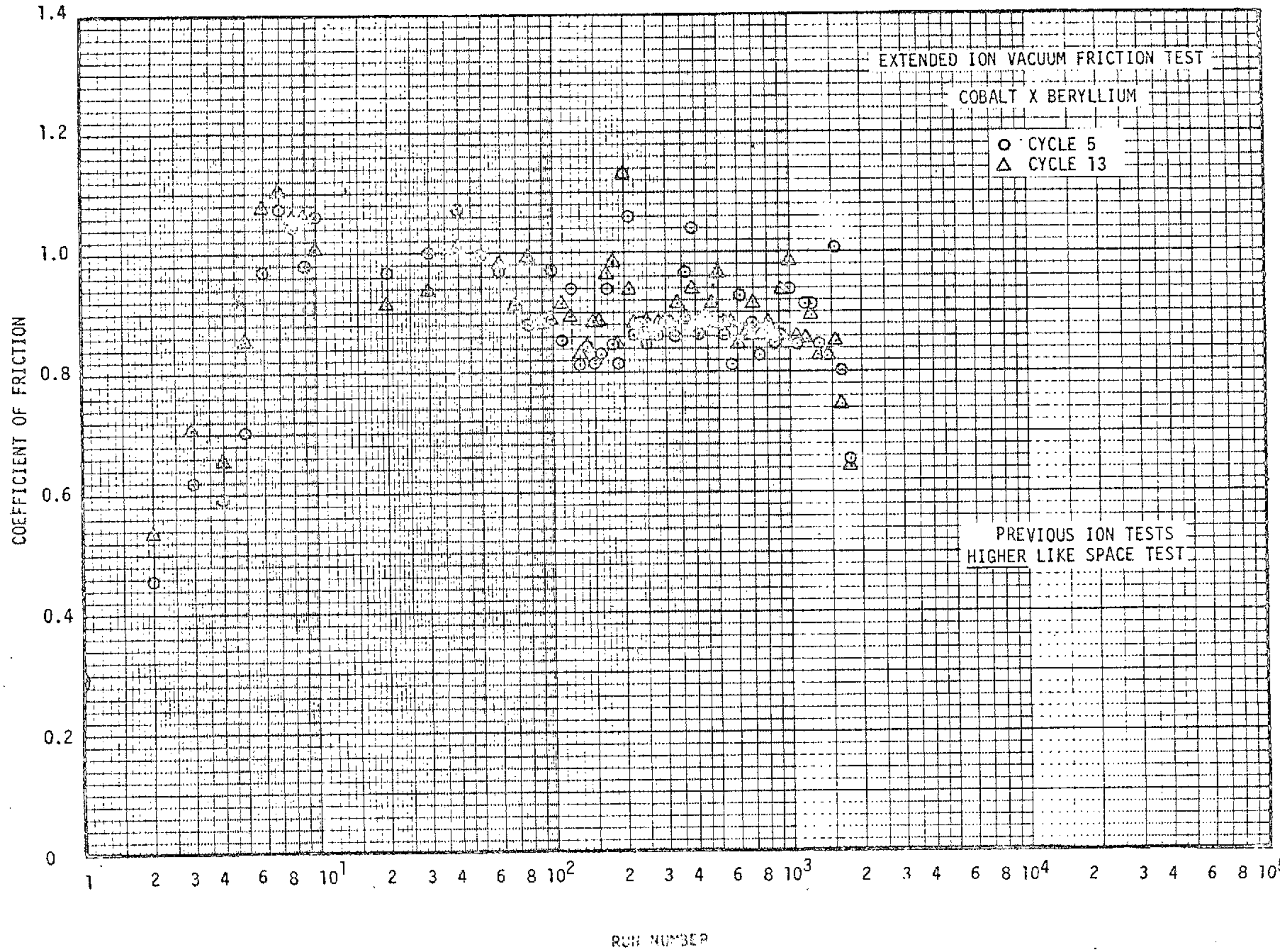
(1 run equals 1 meter of sliding)

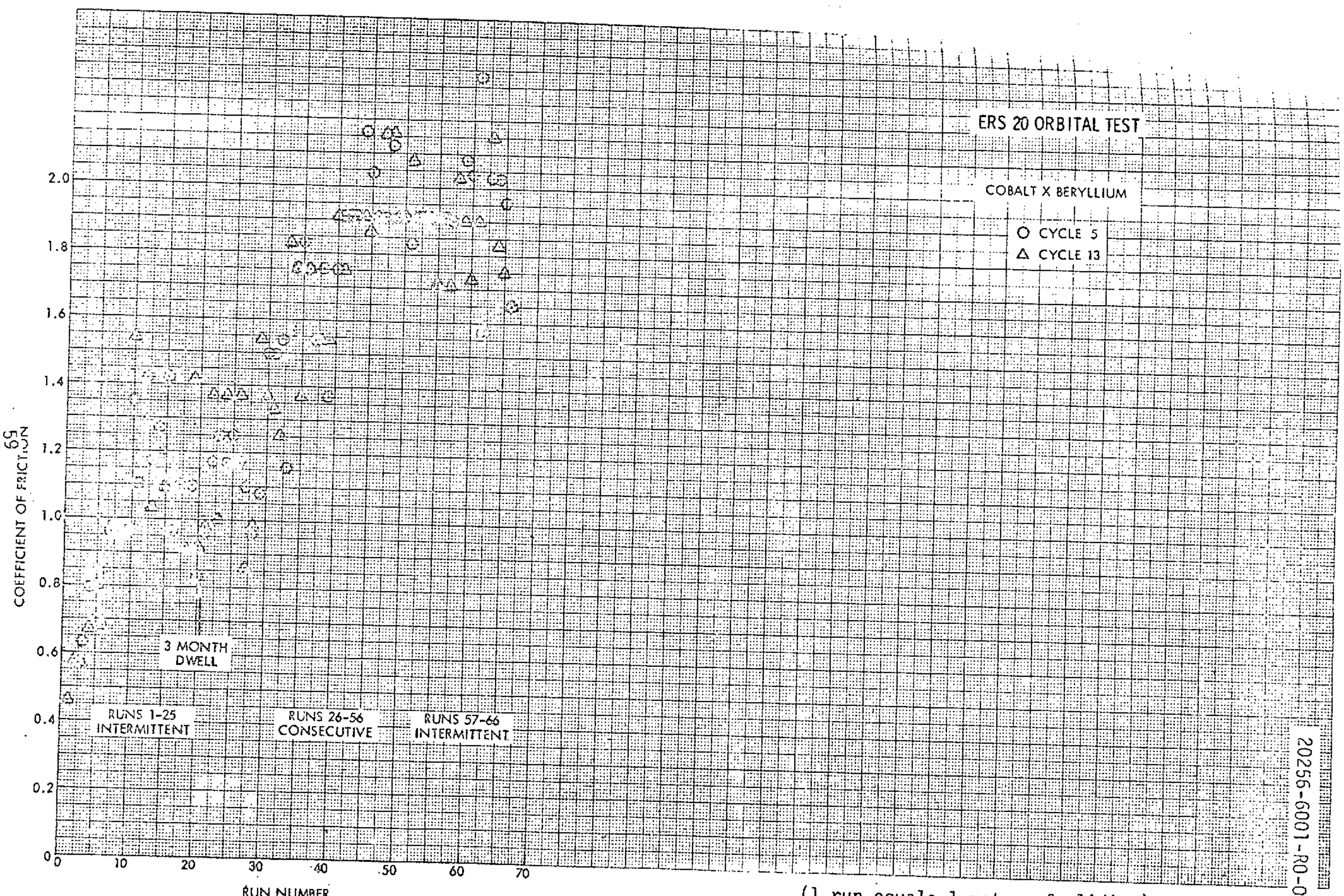

EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X 17-4 PH STAINLESS STEEL
○ CYCLE 4
△ CYCLE 12
INTERRUPTION
COEFFICIENT OF FRICTION
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0

440C STAINLESS STEEL X 17-4 PH STAINLESS STEEL

NO ERS 20 ORBITAL TEST DATA AVAILABLE

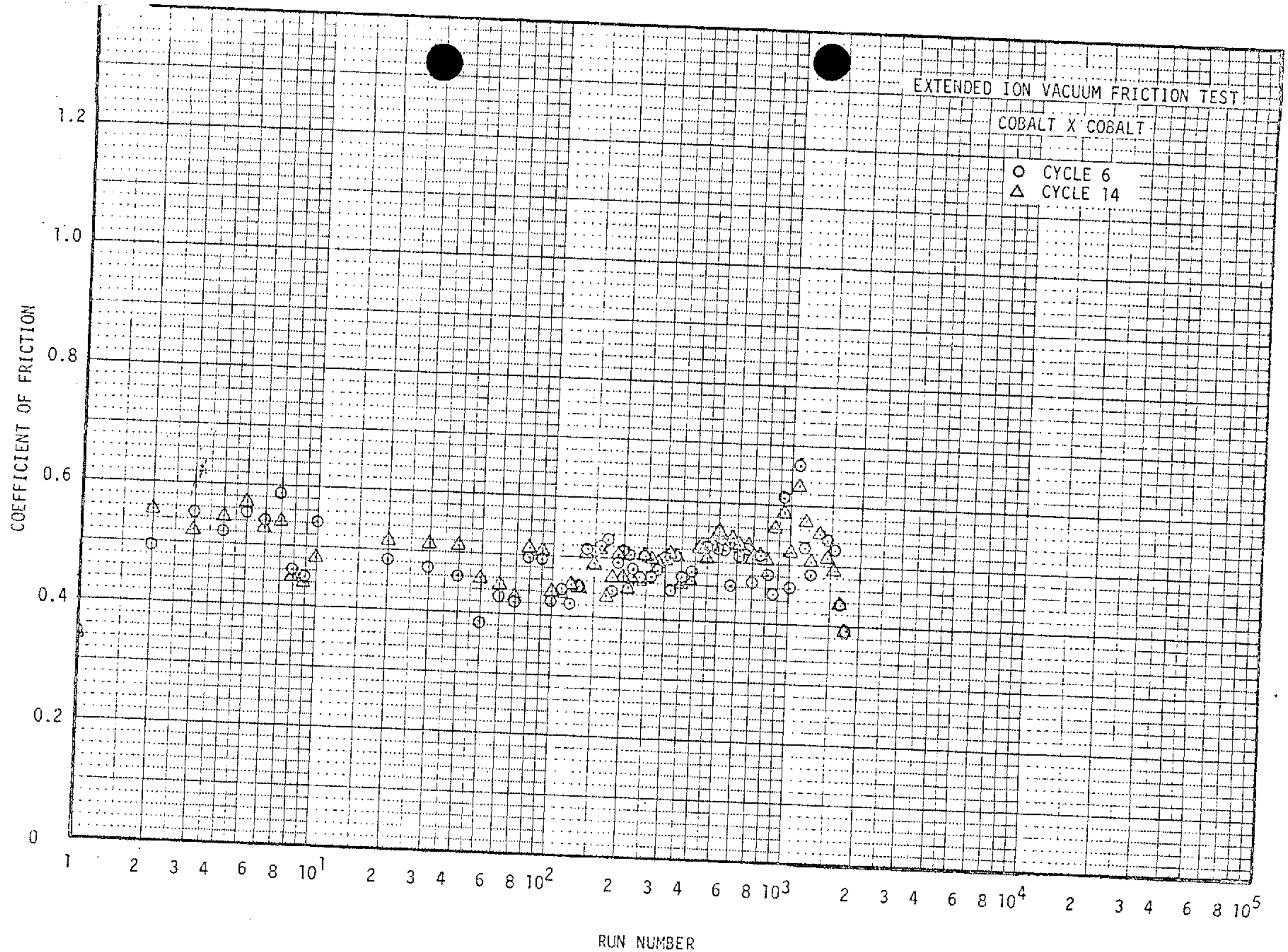
A single initial data point of ~0.1 coefficient of friction was obtained in the flight test. The telemetry data from the spacecraft suggested the shear pin for the flexure arm had released.

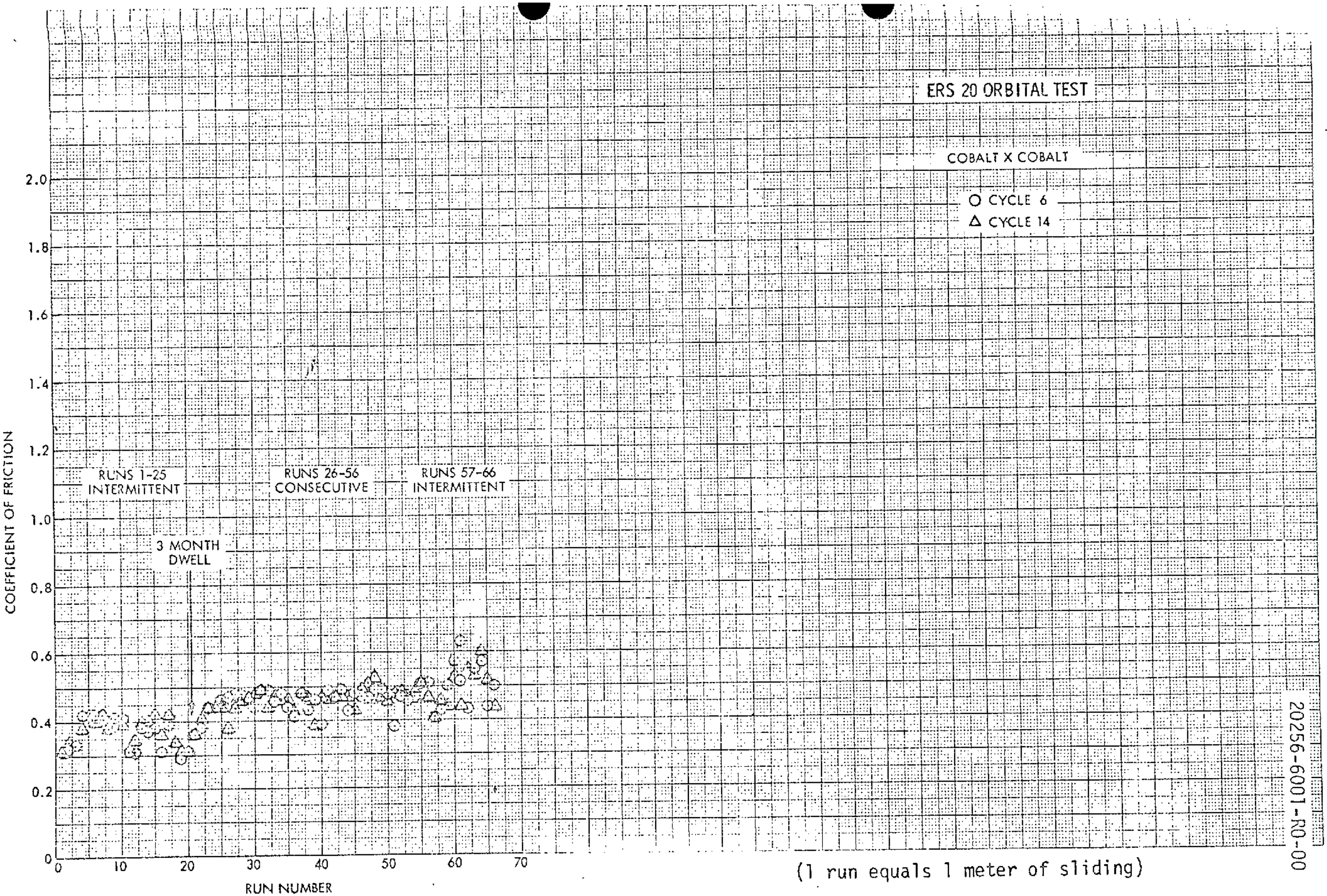

EXTENDED ION VACUUM FRICTION TEST
COBALT X BERYLLIUM
O CYCLE 5
△ CYCLE 13
PREVIOUS ION TESTS
HIGHER LIKE SPACE TEST
COEFFICIENT OF FRICTION
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1 2 3 4 6 8 10¹ 2 3 4 6 8 10² 2 3 4 6 8 10³ 2 3 4 6 8 10⁴ 2 3 4 6 8 10⁵
RUN NUMBER



(1 run equals 1 meter of sliding)

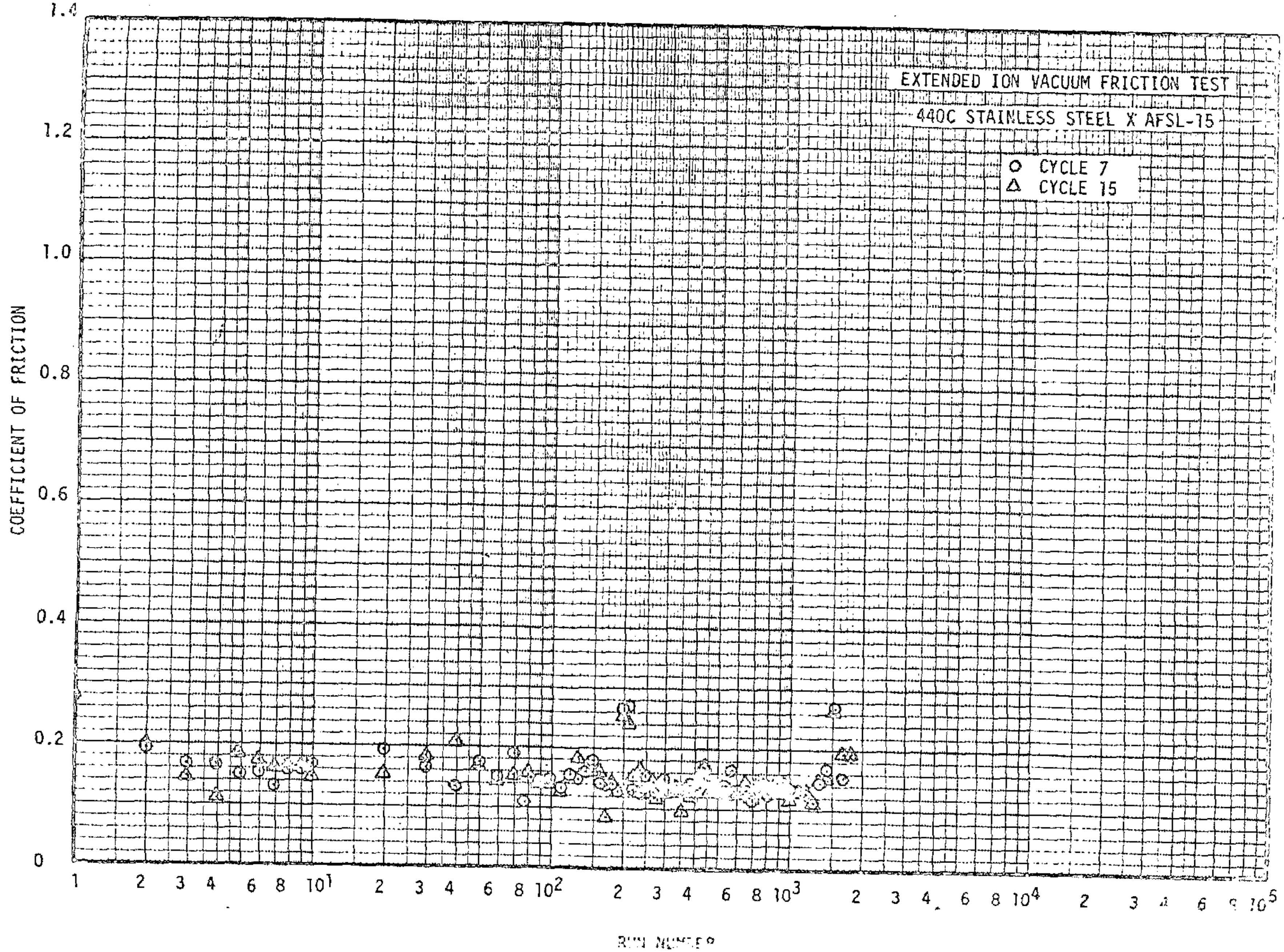
20256-6001-R0-00

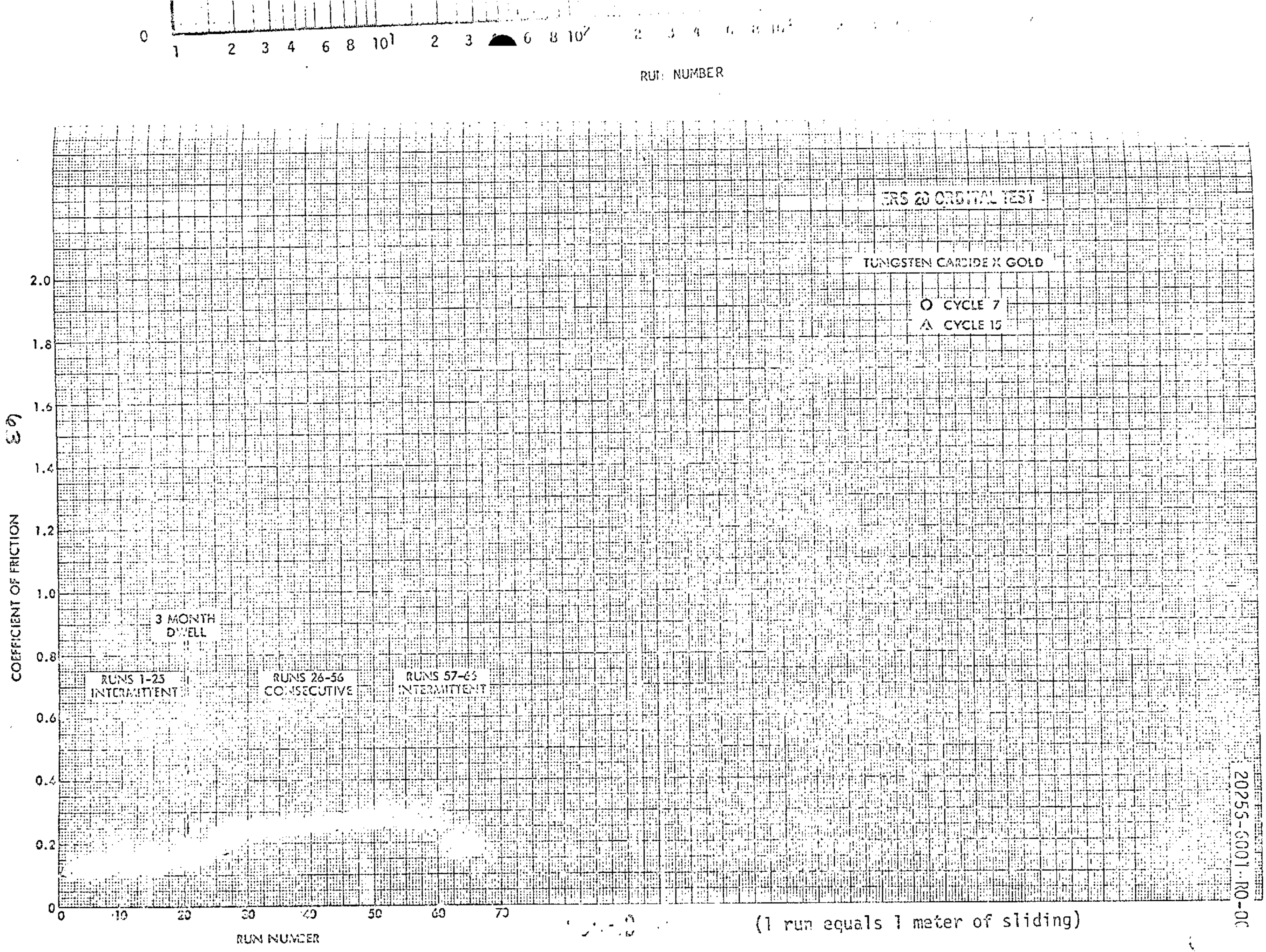

EXTENDED ION VACUUM FRICTION TEST
COBALT X COBALT
○ CYCLE 6
△ CYCLE 14
COEFFICIENT OF FRICTION
0
0.2
0.4
0.6
0.8
1.0
1.2
RUN NUMBER
1
2 3 4 6 8 10^1
2 3 4 6 8 10^2
2 3 4 6 8 10^3
2 3 4 6 8 10^4
2 3 4 6 8 10^5



(1 run equals 1 meter of sliding)

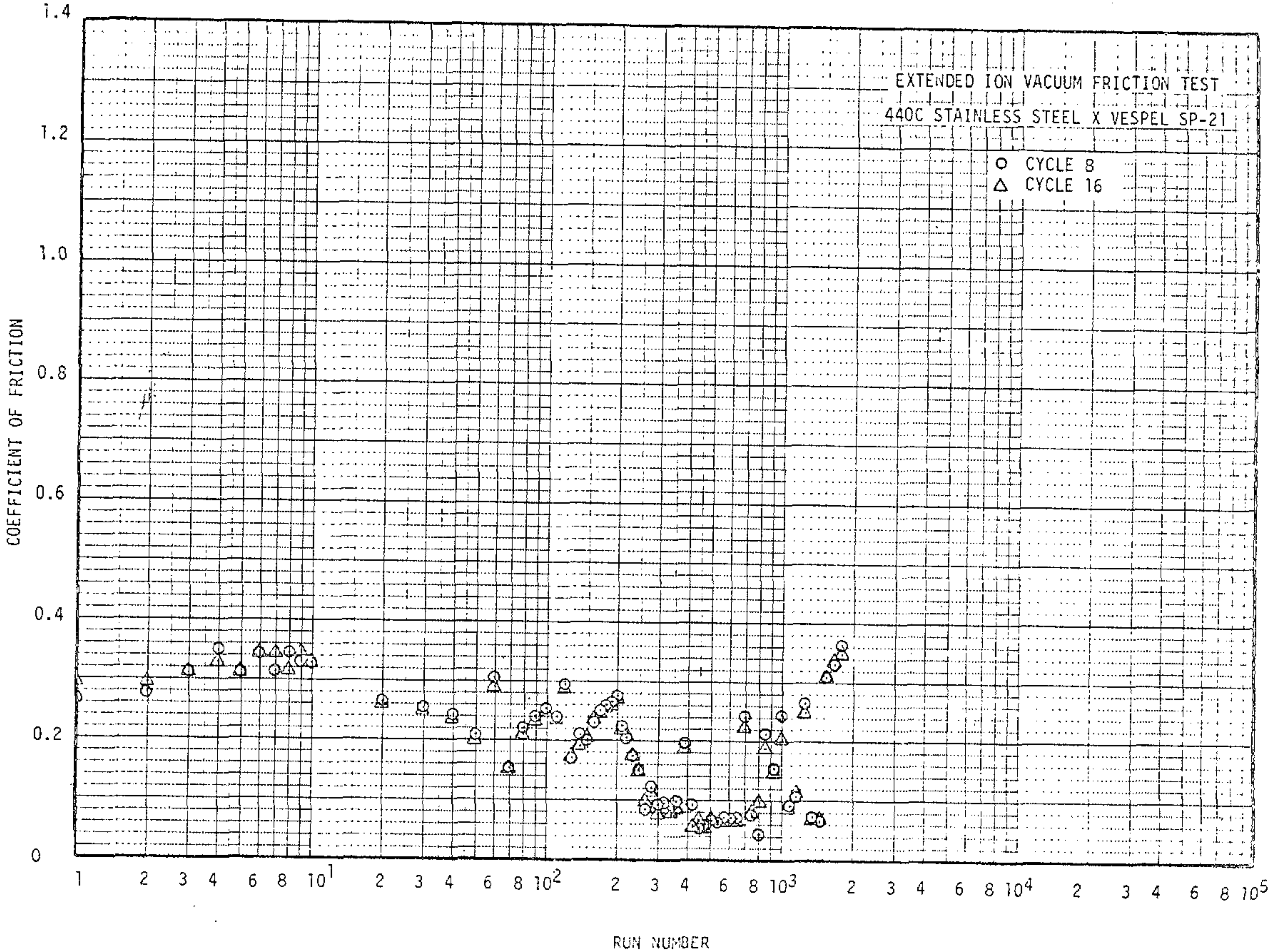
20256-6001-R0-00

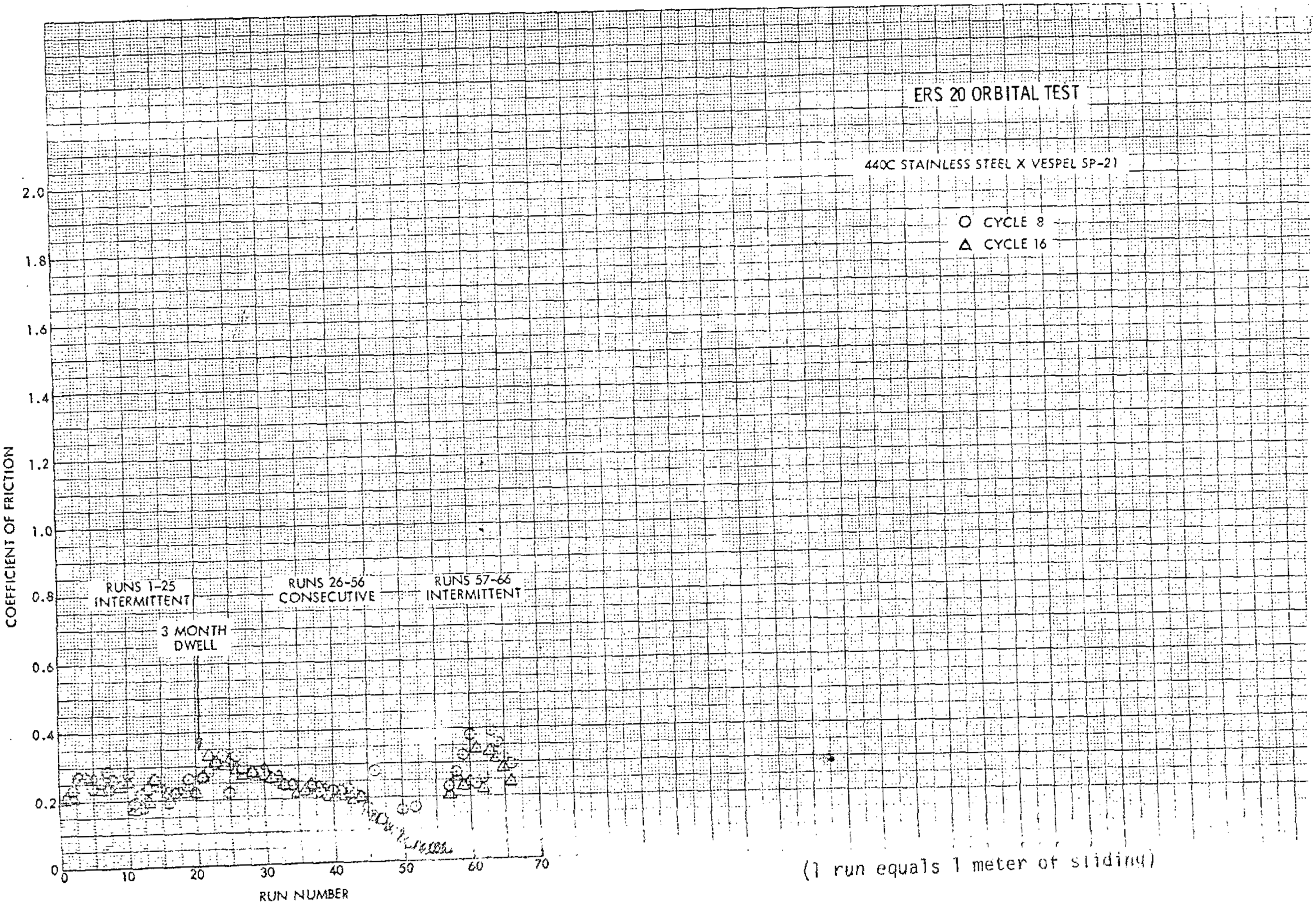

EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X AFSL-15
O CYCLE 7
Δ CYCLE 15
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 6 10^5



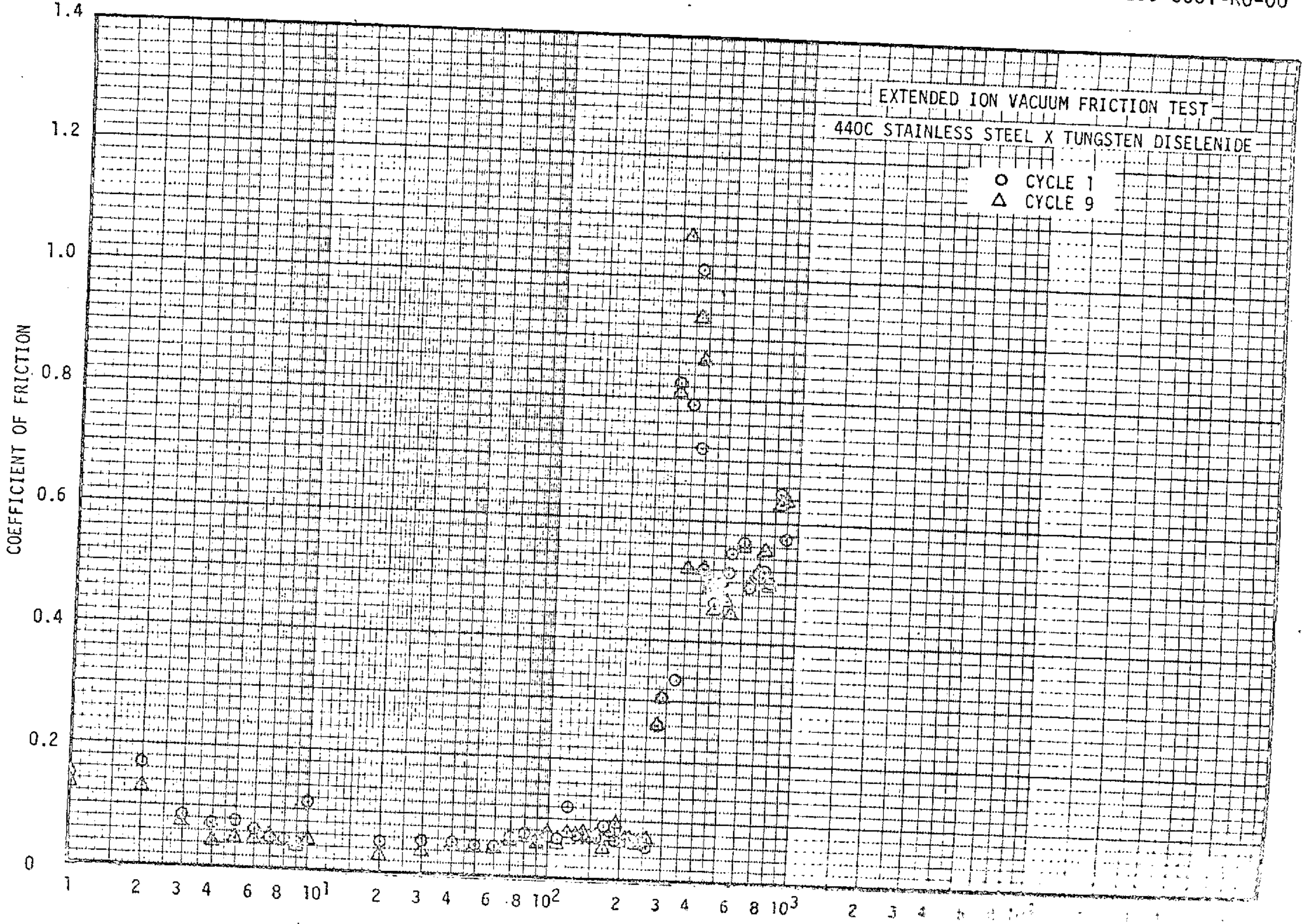
(1 run equals 1 meter of sliding)

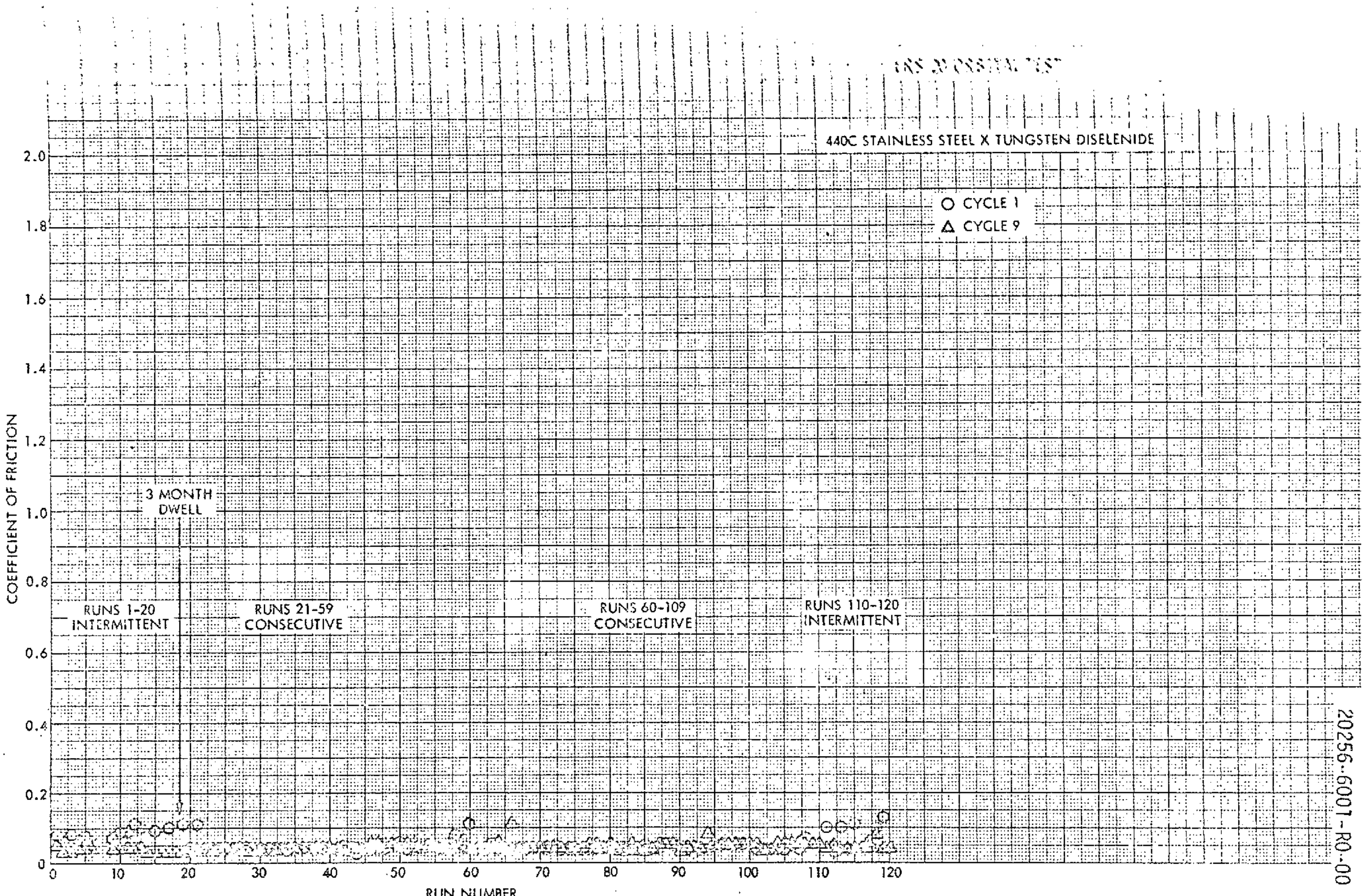
20255-6001-RO-00


EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X VESPEL SP-21
CYCLE 8
CYCLE 16
COEFFICIENT OF FRICTION
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 4 6 8 10^5
RUN NUMBER



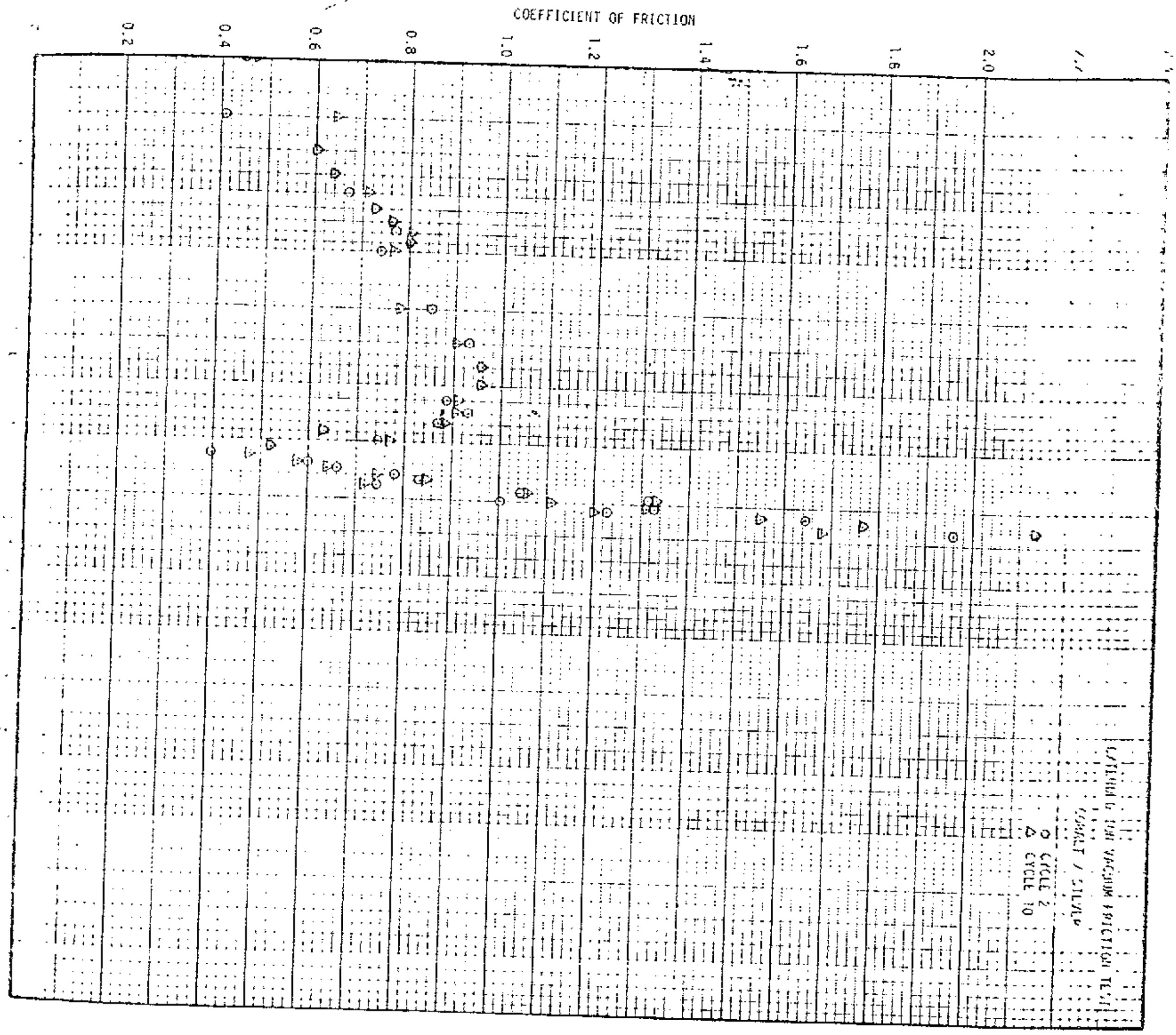
(1 run equals 1 meter of sliding)

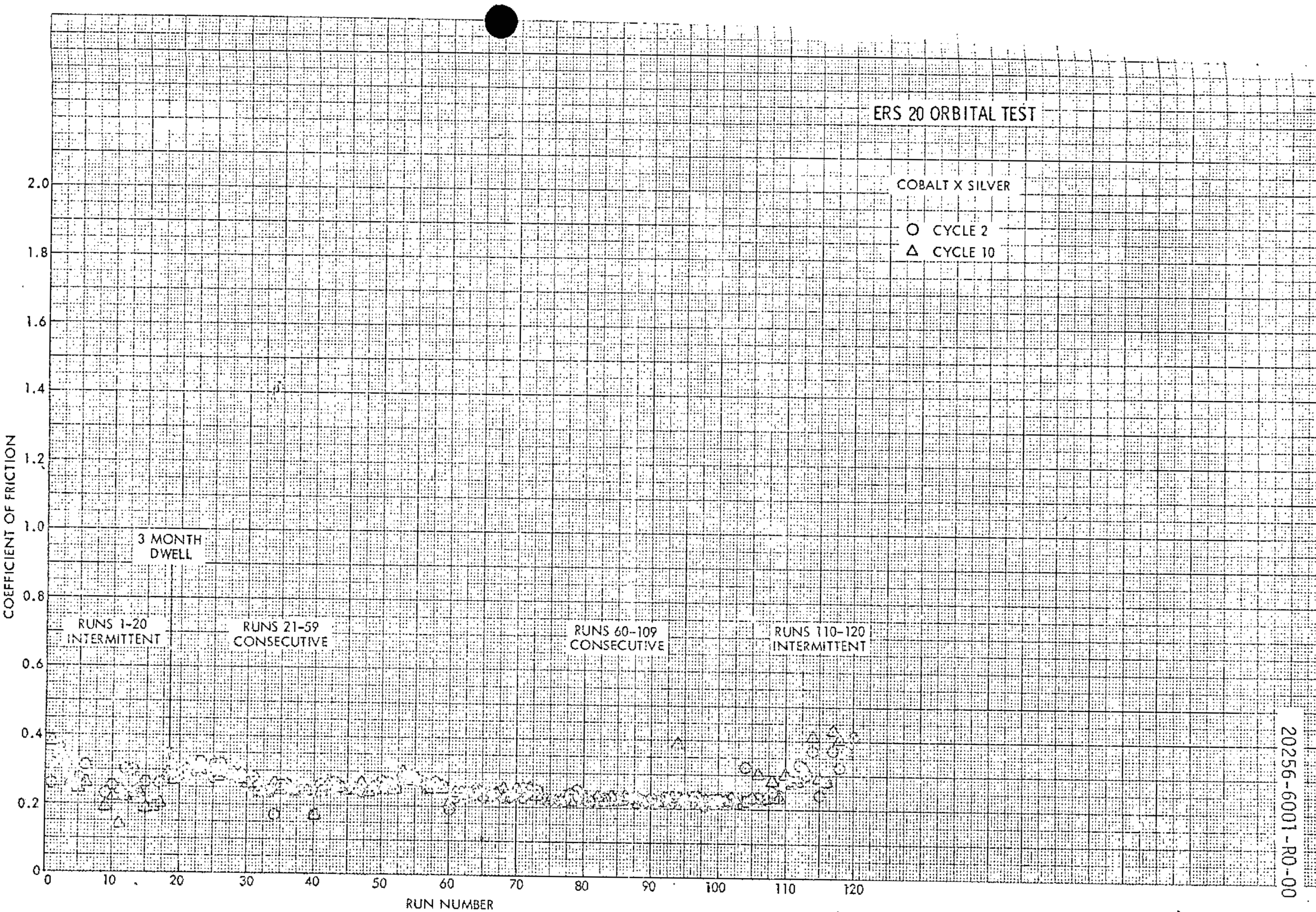

EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X TUNGSTEN DISELENIDE
O CYCLE 1
Δ CYCLE 9
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1 2 3 4 6 8 10¹ 2 3 4 6 8 10² 2 3 4 6 8 10³ 2 3 4



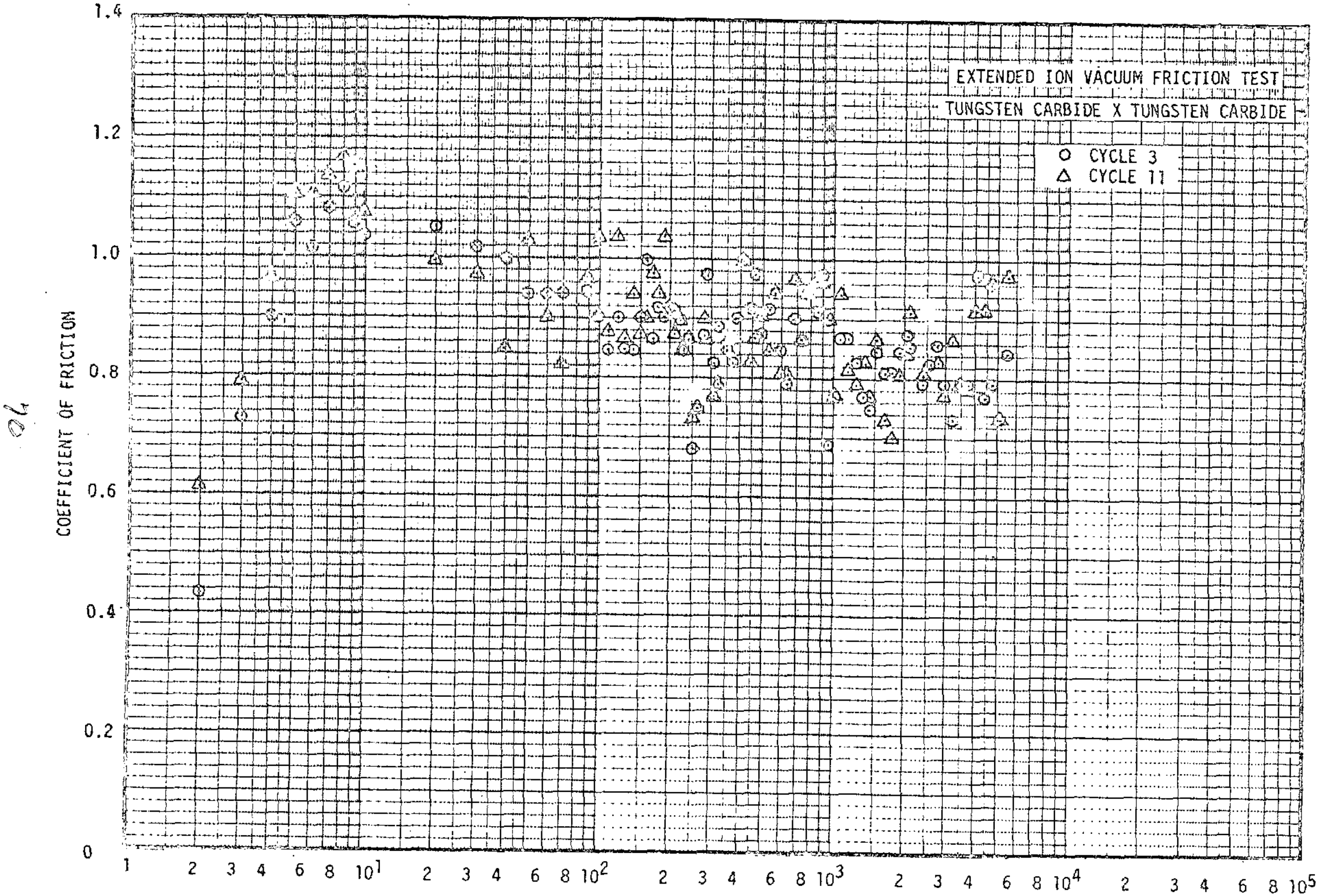
(1 run equals 1 meter of sliding)

20256-6001-R0-00

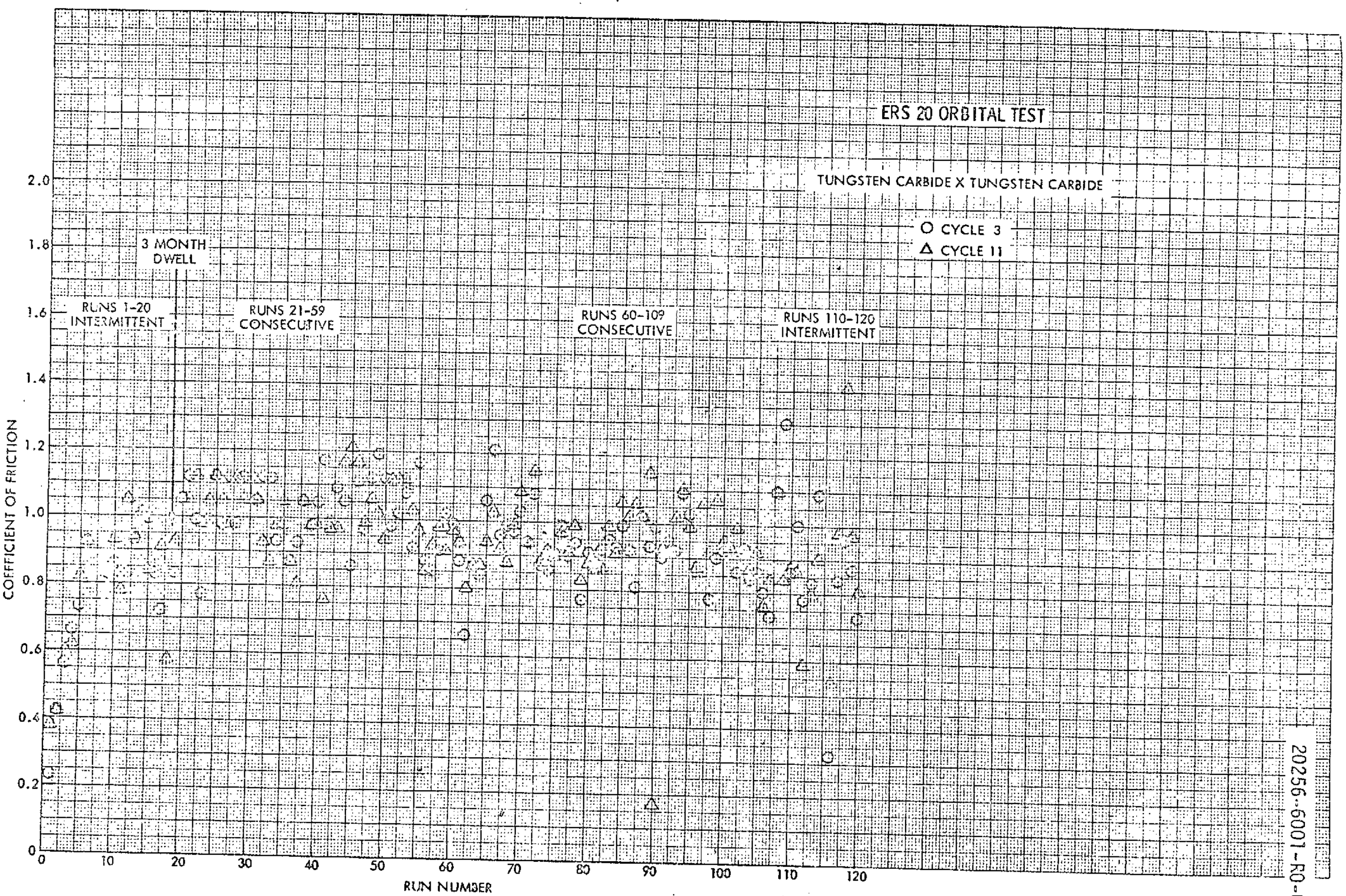

COEFFICIENT OF FRICTION
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
COBALT / SILVER
CYCLE 2
CYCLE 10



(1 run equals 1 meter of sliding)

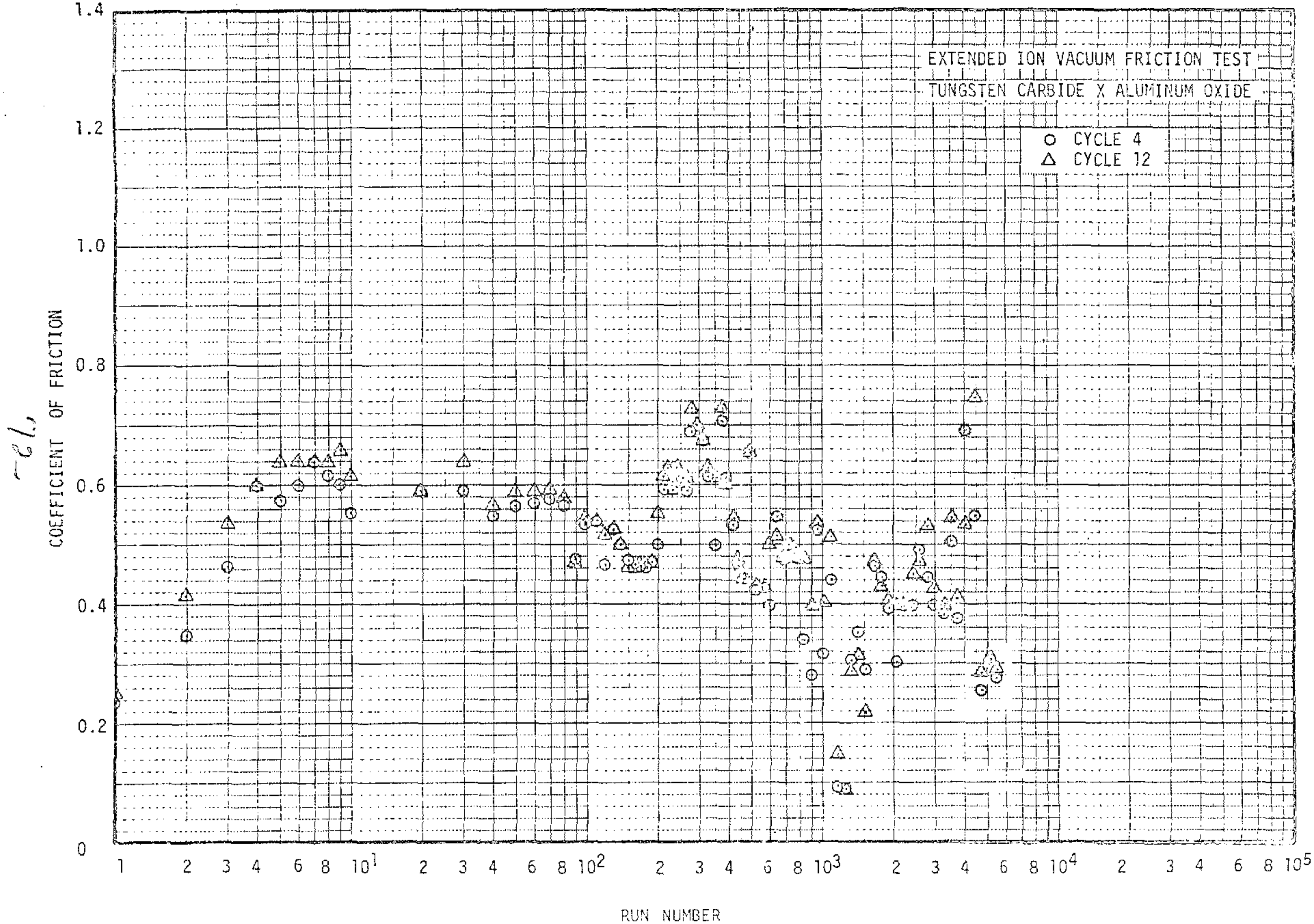


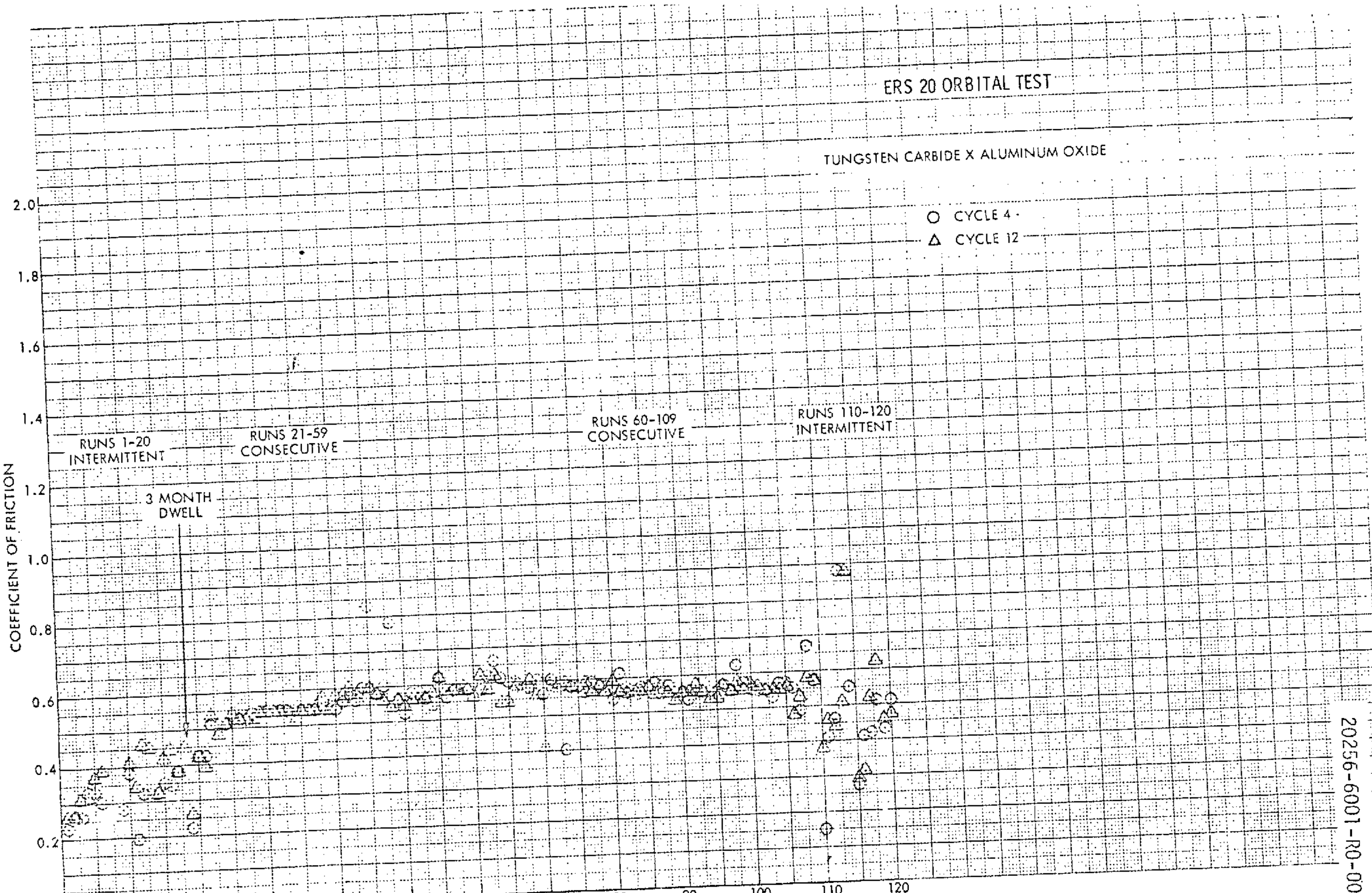
EXTENDED ION VACUUM FRICTION TEST
TUNGSTEN CARBIDE X TUNGSTEN CARBIDE
CYCLE 3
CYCLE 11
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
6
8
10^1
10^2
10^3
10^4
10^5



(1 run equals 1 meter of sliding)

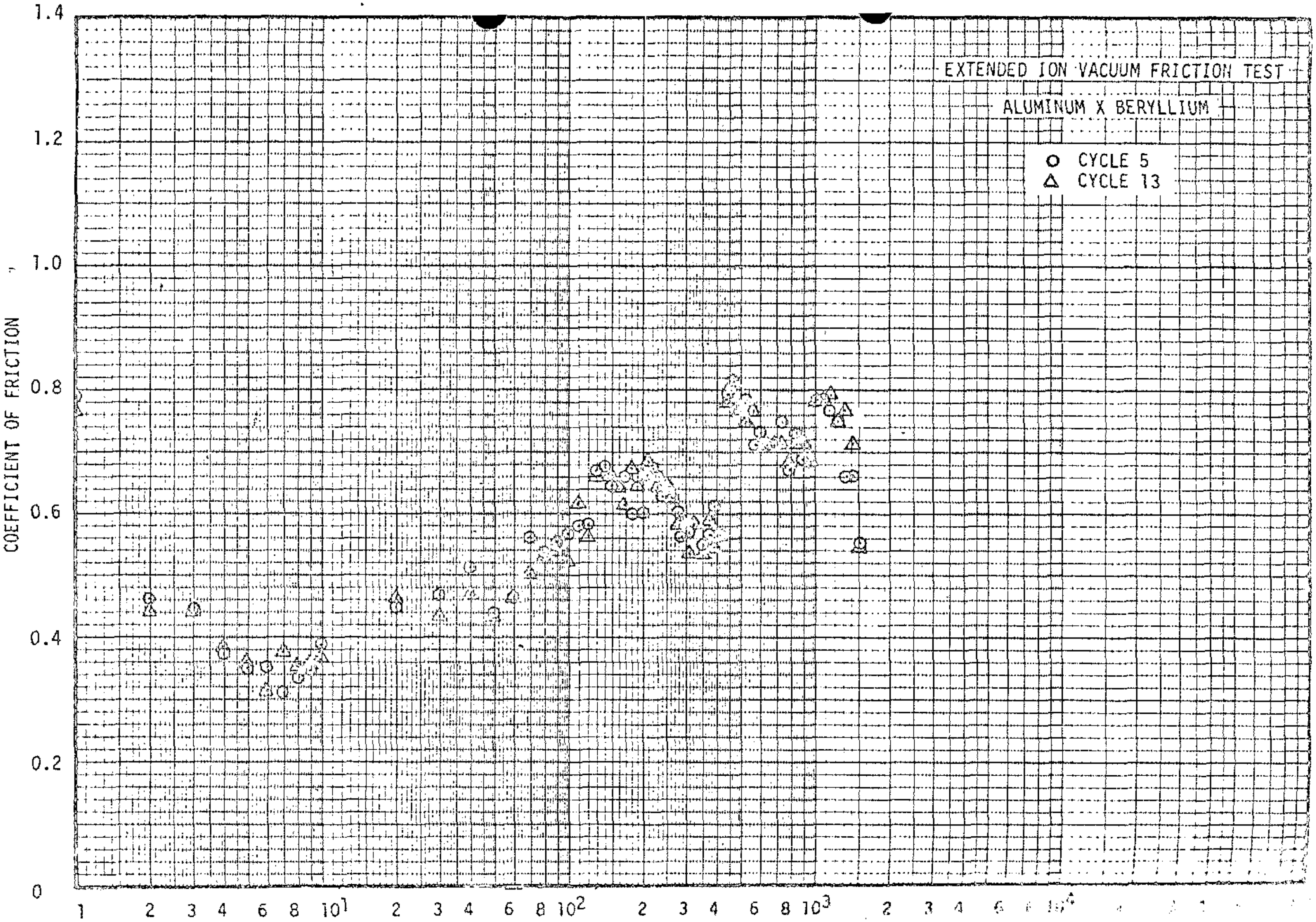
20256-6001-R0-00

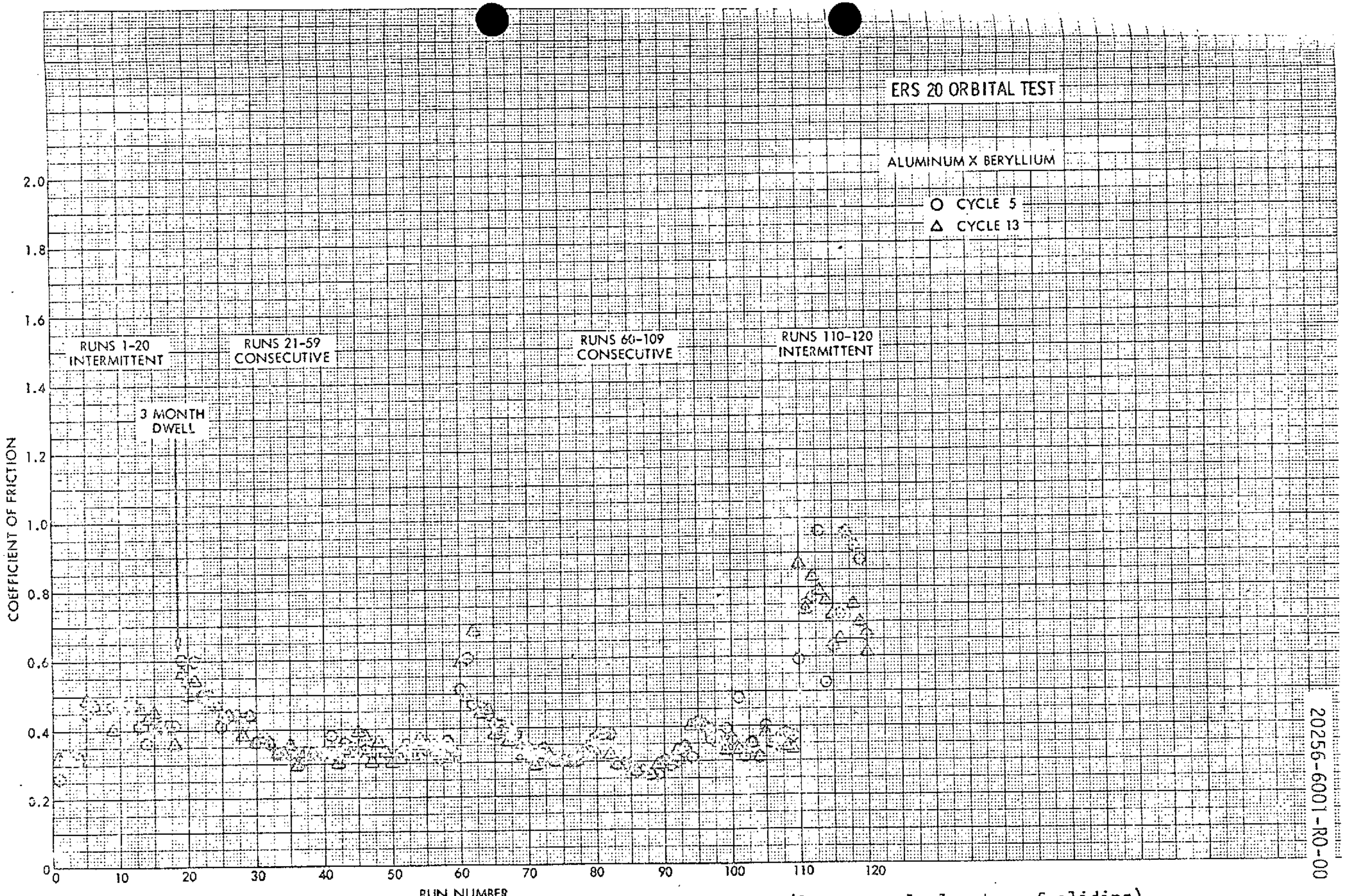

EXTENDED ION VACUUM FRICTION TEST
TUNGSTEN CARBIDE X ALUMINUM OXIDE
CYCLE 4
CYCLE 12
COEFFICIENT OF FRICTION
RUN NUMBER
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 4 6 8 10^5



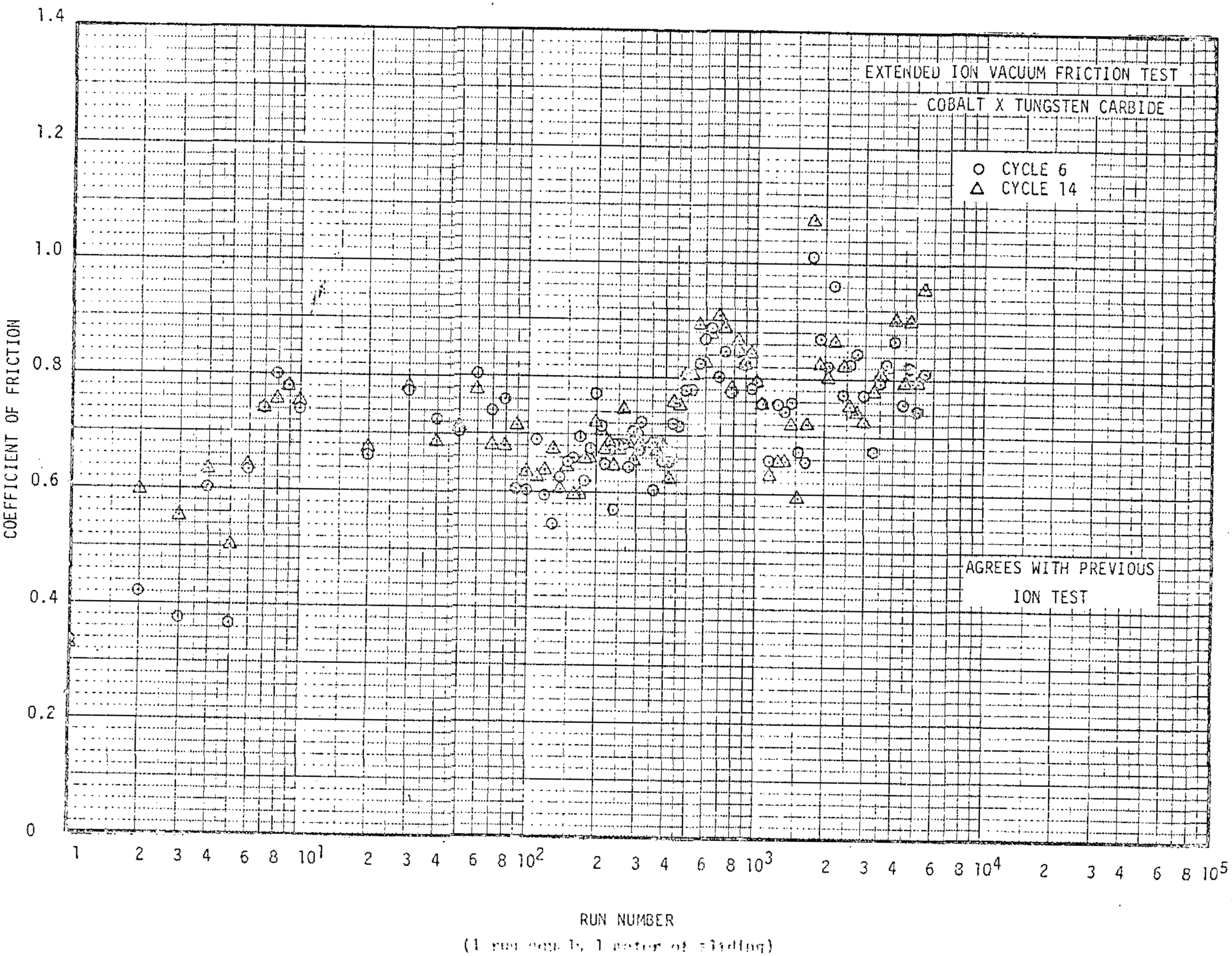
(1 run equals 1 meter of sliding)

20256-6001-R0-00

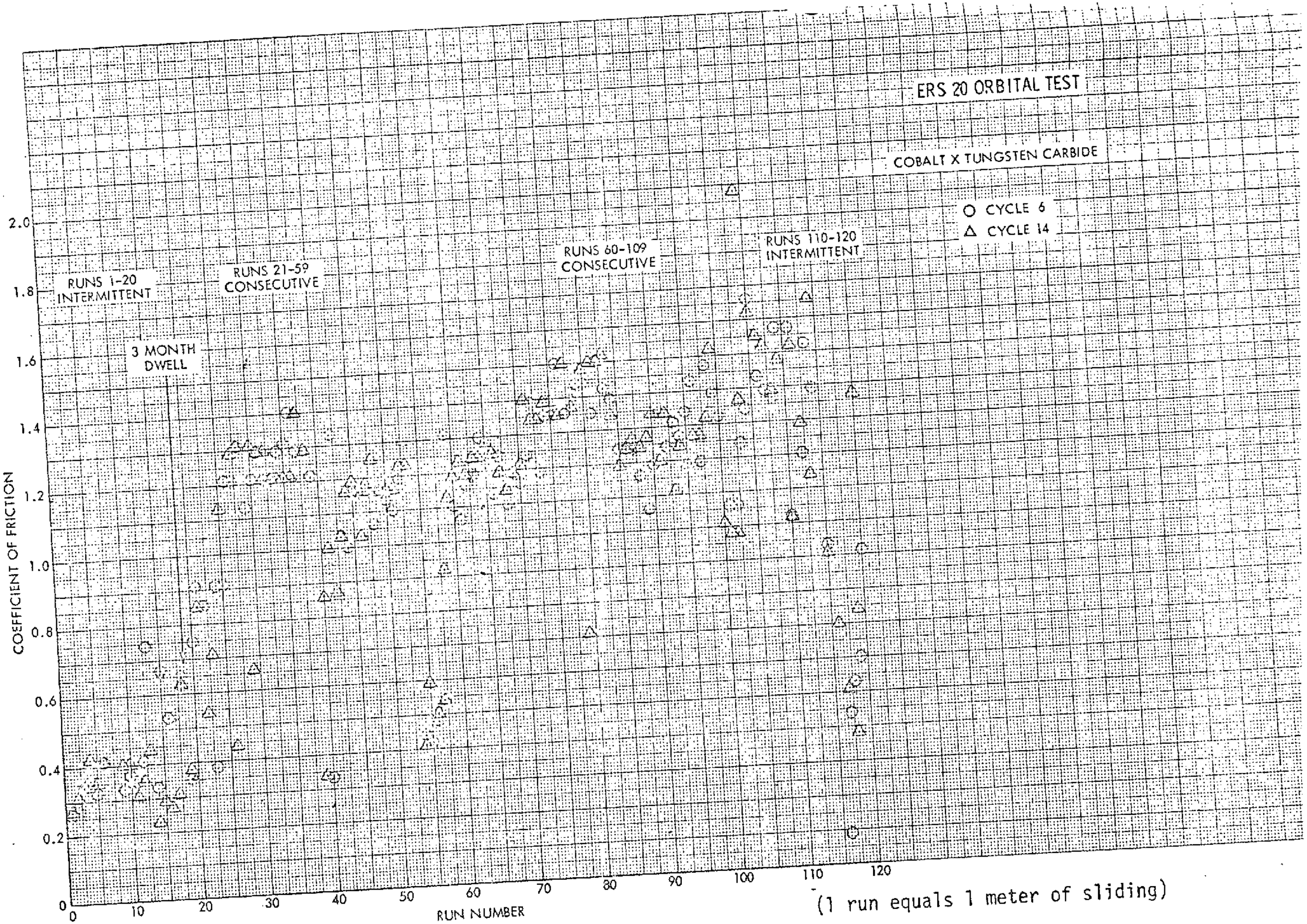

EXTENDED ION VACUUM FRICTION TEST
ALUMINUM X BERYLLIUM
O CYCLE 5
Δ CYCLE 13
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
6
8
10^1
2
3
4
6
8
10^2
2
3
4
6
8
10^3
2
3
4

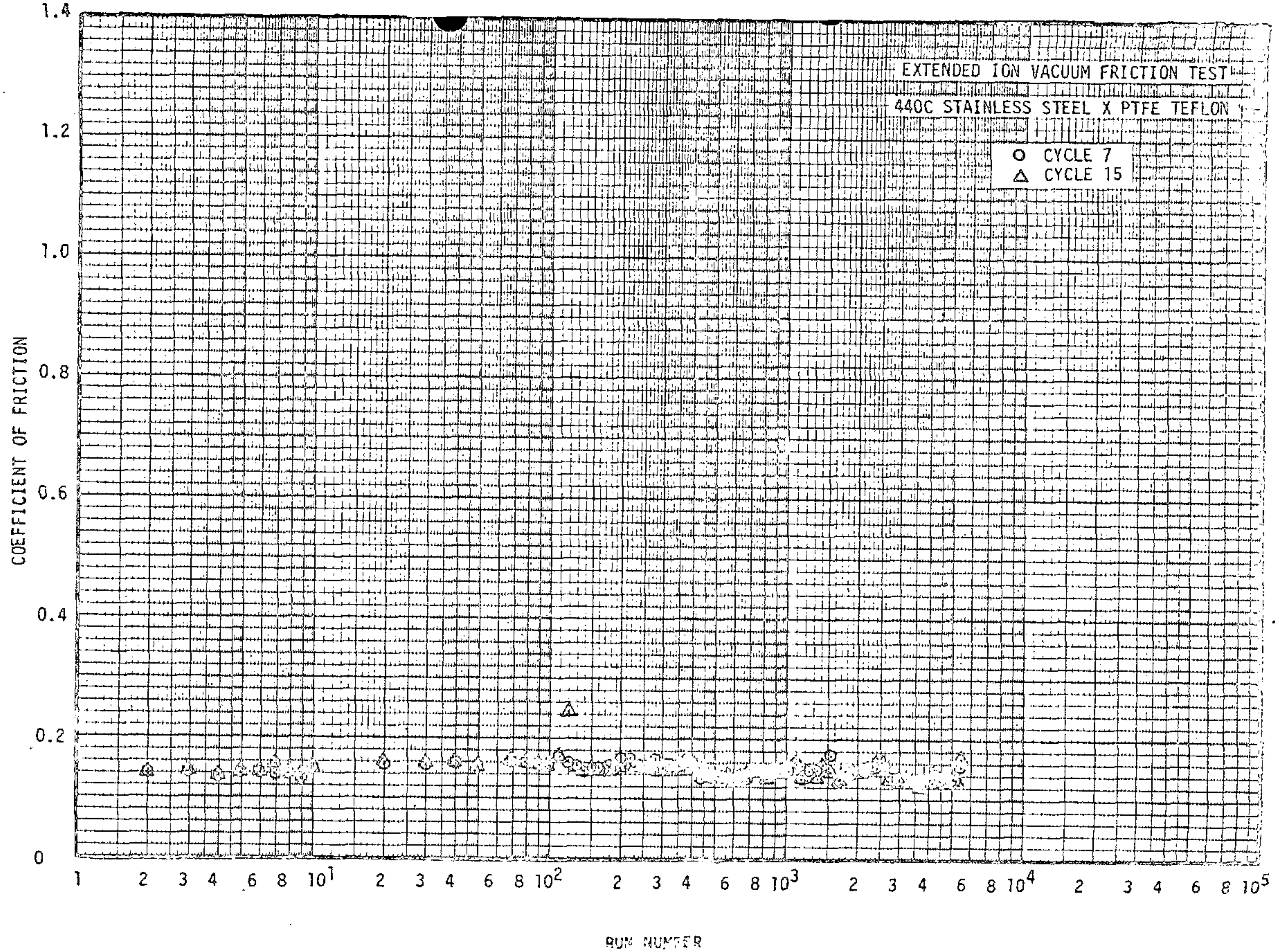


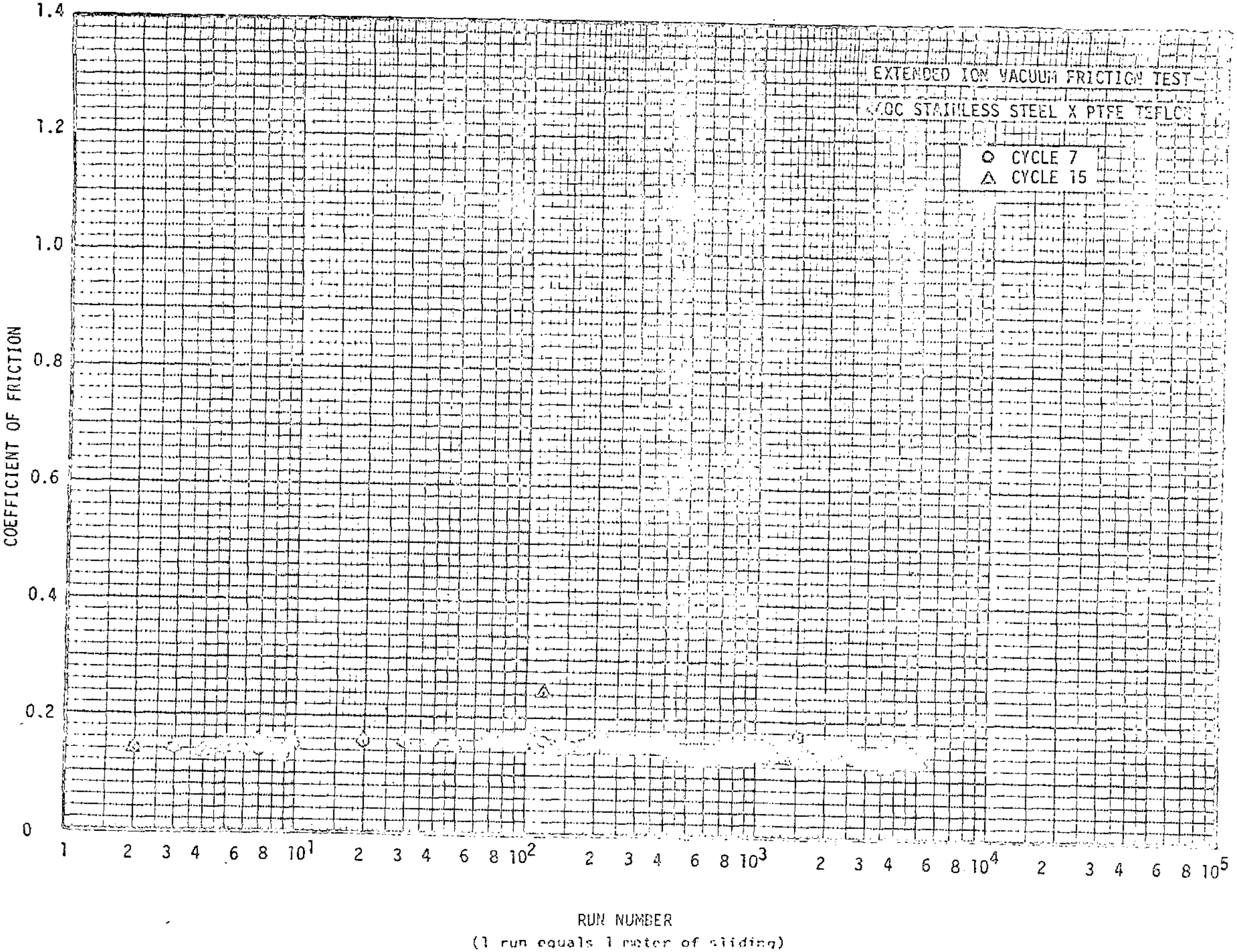
(1 run equals 1 meter of sliding)

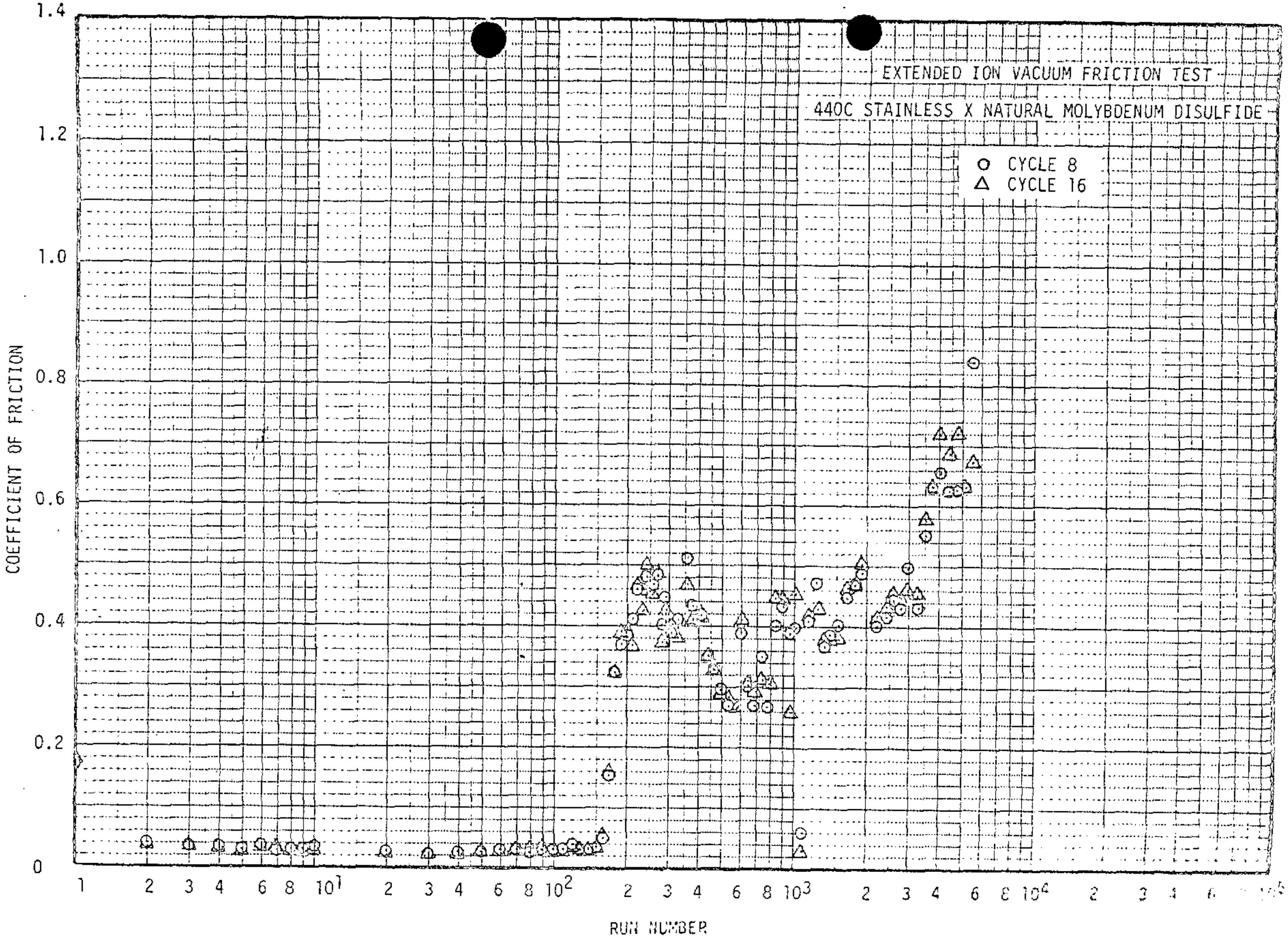

EXTENDED ION VACUUM FRICTION TEST
COBALT X TUNGSTEN CARBIDE
CYCLE 6
CYCLE 14
AGREES WITH PREVIOUS ION TEST
COEFFICIENT OF FRICTION
RUN NUMBER
(1 run equals 1 meter of sliding)

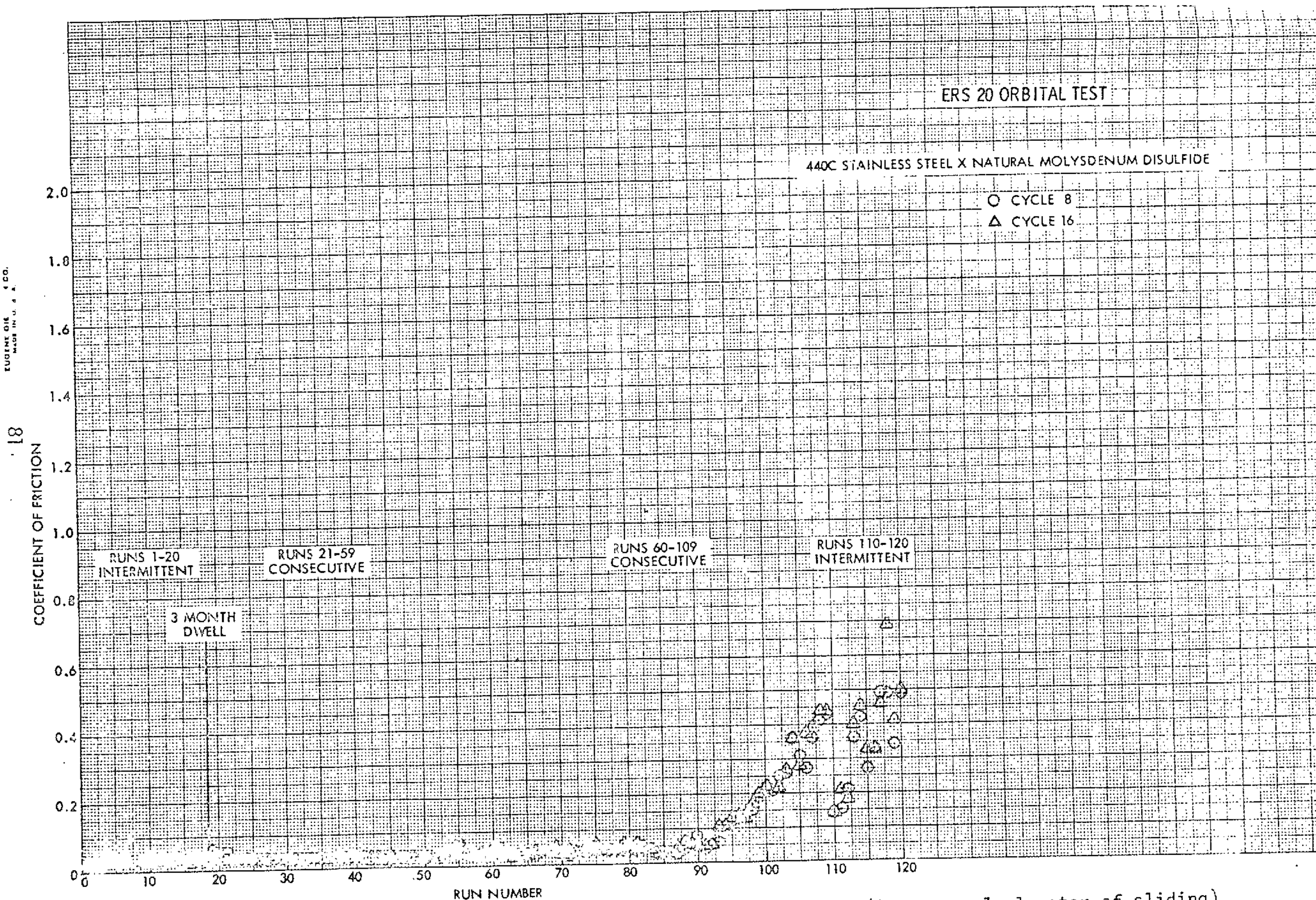
(1 run equals 1 meter




EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X PTFE TEFLON
O CYCLE 7
△ CYCLE 15
COEFFICIENT OF FRICTION
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 4 6 8 10^5
RUN NUMBER


EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS STEEL X PTFE TEFLON
CYCLE 7
CYCLE 15
COEFFICIENT OF FRICTION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1 2 3 4 6 8 10^1 2 3 4 6 8 10^2 2 3 4 6 8 10^3 2 3 4 6 8 10^4 2 3 4 6 8 10^5
RUN NUMBER
(1 run equals 1 meter of sliding)


EXTENDED ION VACUUM FRICTION TEST
440C STAINLESS X NATURAL MOLYBDENUM DISULFIDE
O CYCLE 8
Δ CYCLE 16
COEFFICIENT OF FRICTION
RUN NUMBER
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1
2 3 4 6 8 10^1
2 3 4 6 8 10^2
2 3 4 6 8 10^3
2 3 4 6 8 10^4



(1 run equals 1 meter of sliding)

APPENDIX B
OIL PUMPED FRICTION DATA

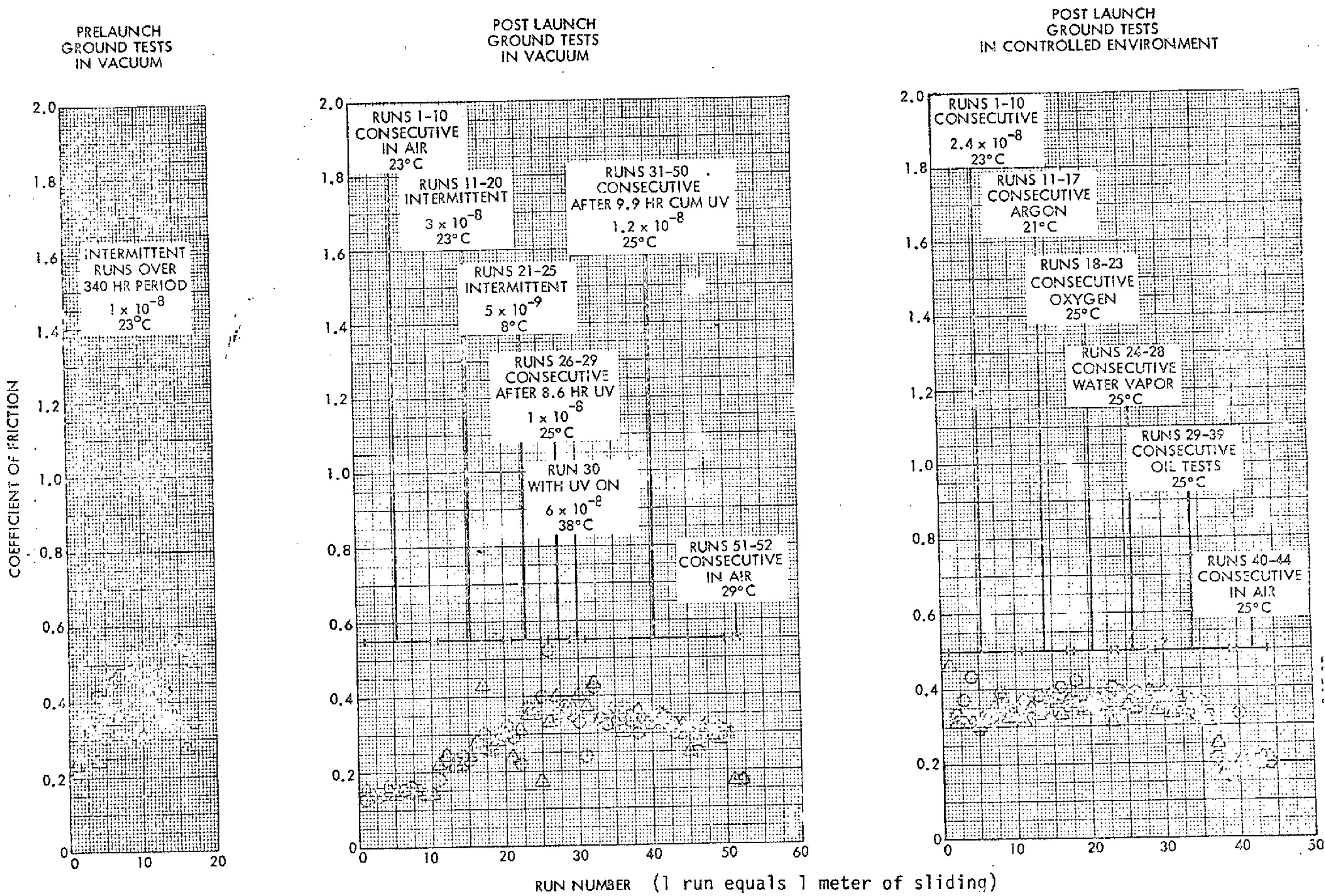
This section contains composite graphs of the ground friction data for sixteen material combinations studied under contract AF 04(611)-10747. The study used a TRW oil diffusion pumped ultrahigh vacuum chamber to provide the test environment. Three sets of ground test data were generated from the prelaunch, post launch and controlled environment tests. The facility, procedures and discussion of the results are contained in AFRPL-TR-69-207, Reference 2.

Results of the ground tests are shown here to allow comparison with results shown in Appendix A, C & D.

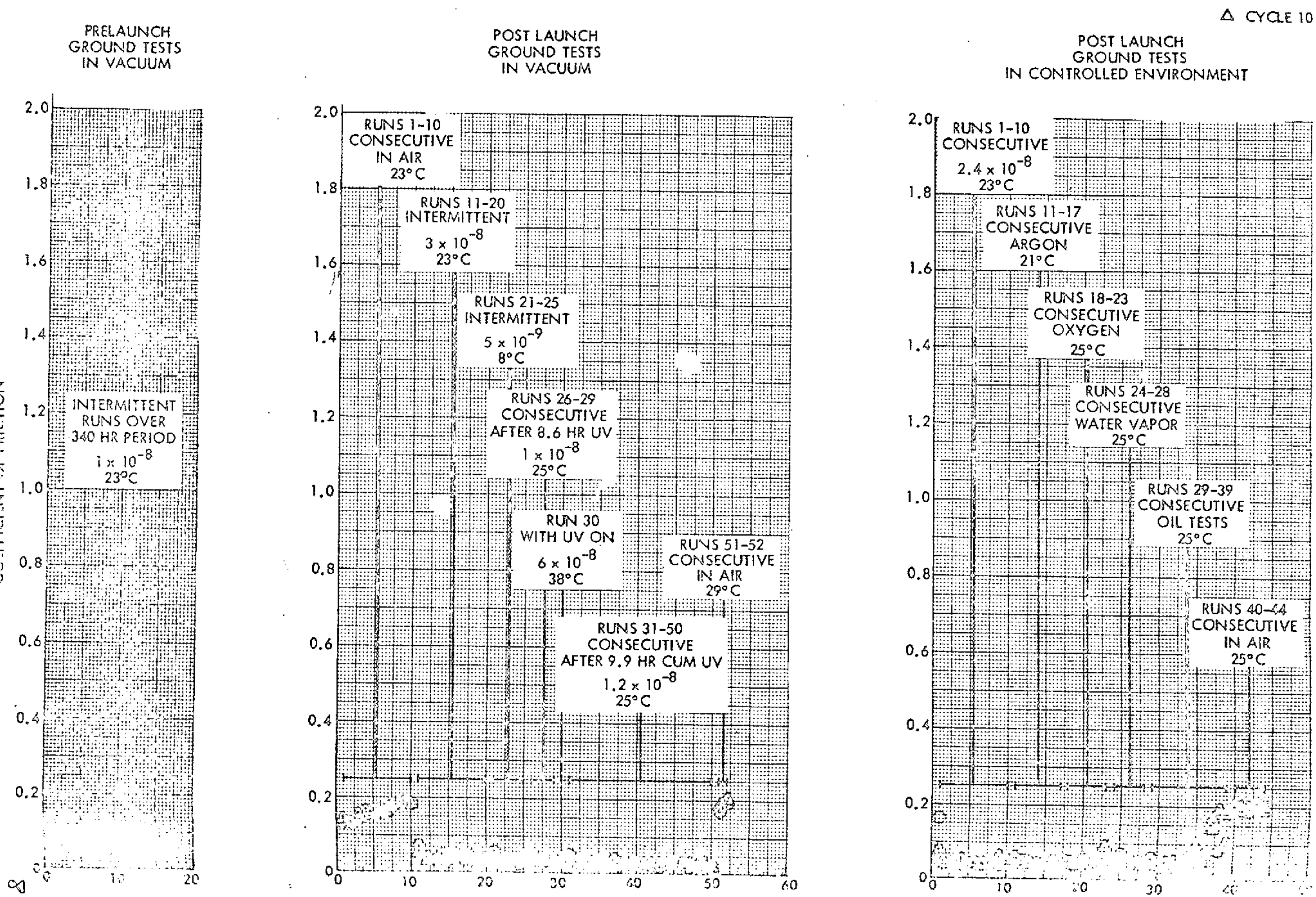
The order of presentation is by designation on the modules A1-8 and 1-8.

<u>Page</u>

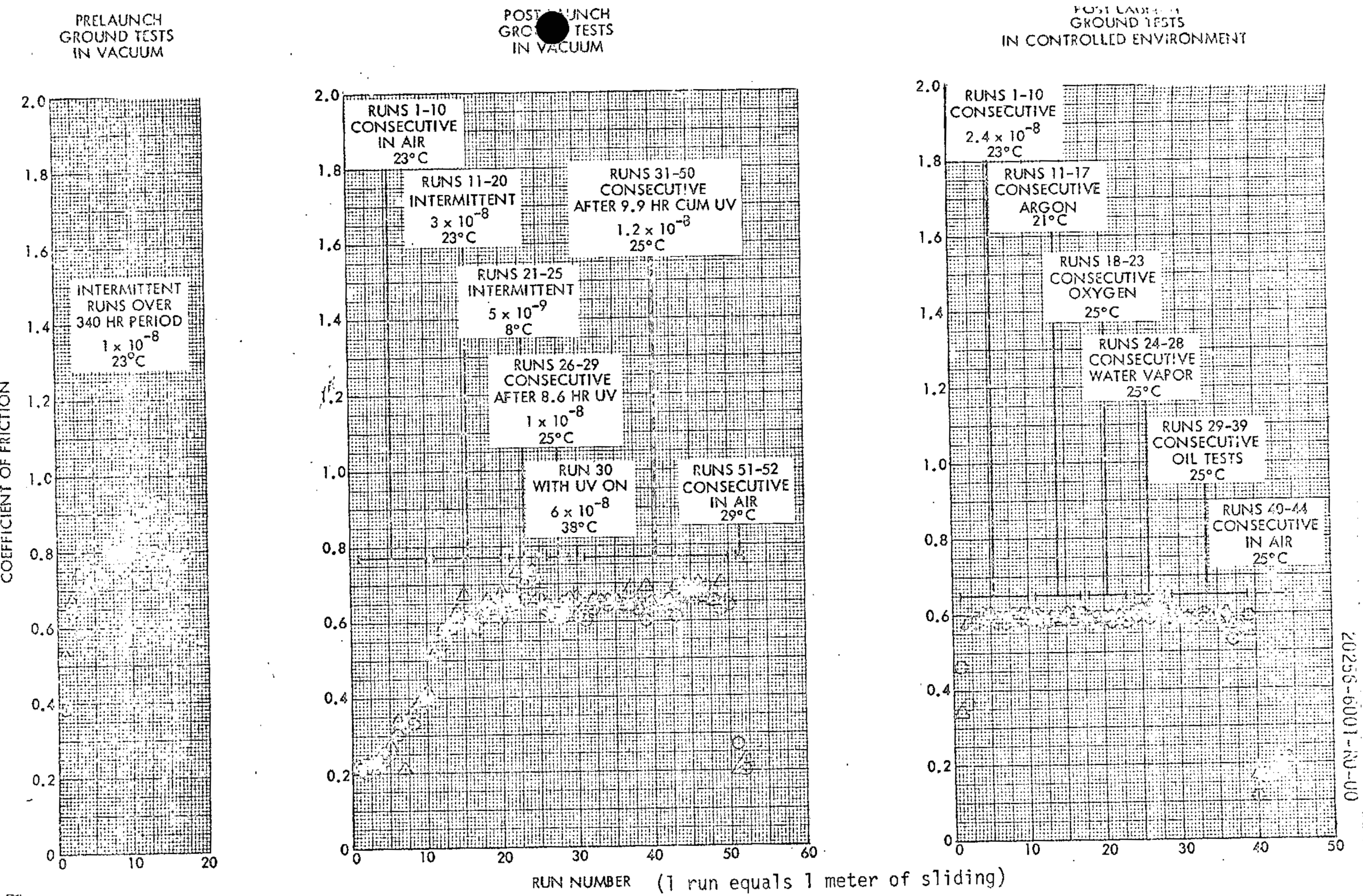
440C STAINLESS STEEL X BORON NITRIDE



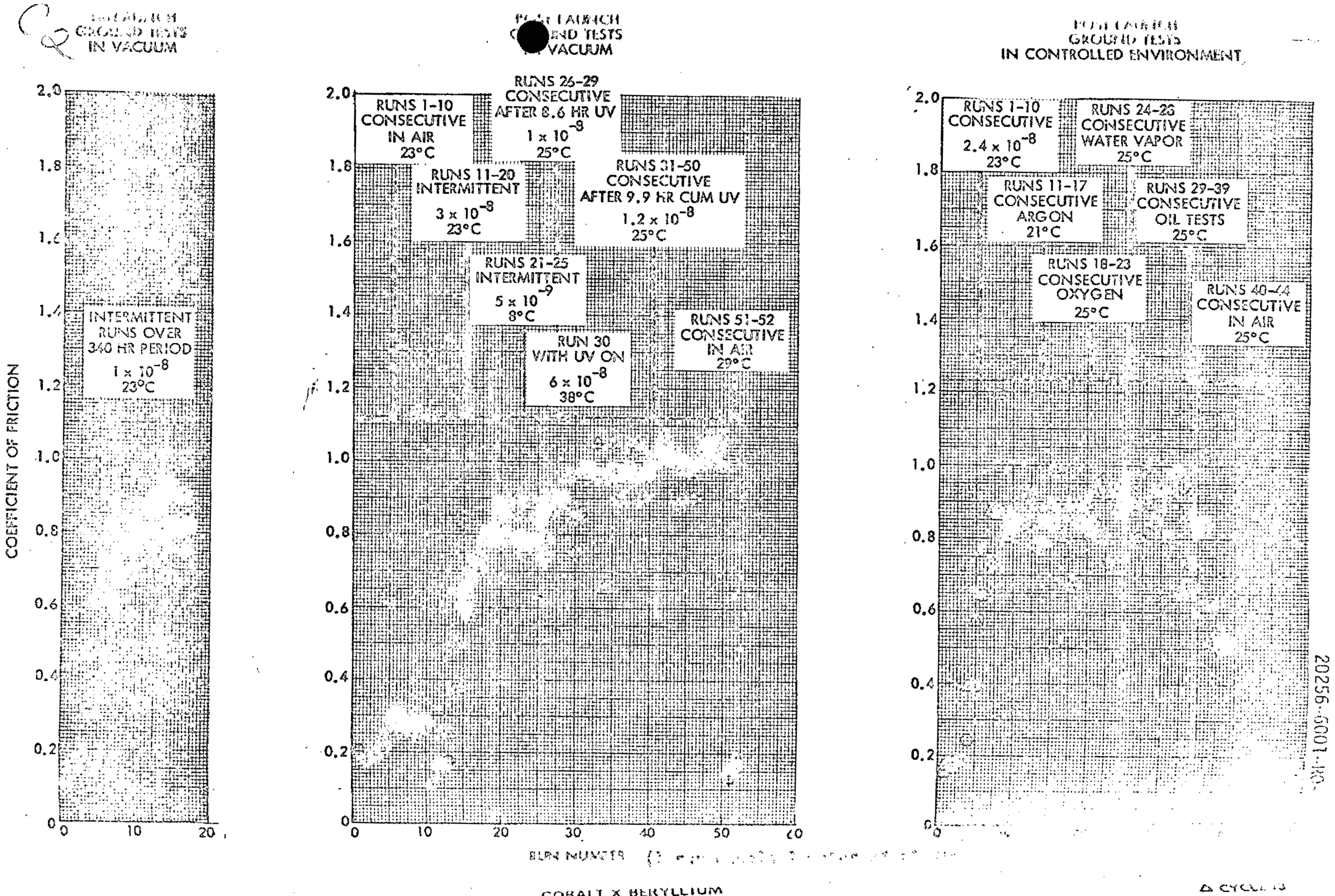
440C STAINLESS STEEL X SYNTHETIC MOLYBDENUM DISULFIDE



20256-6001-R0-00



20256-6001-RU-00

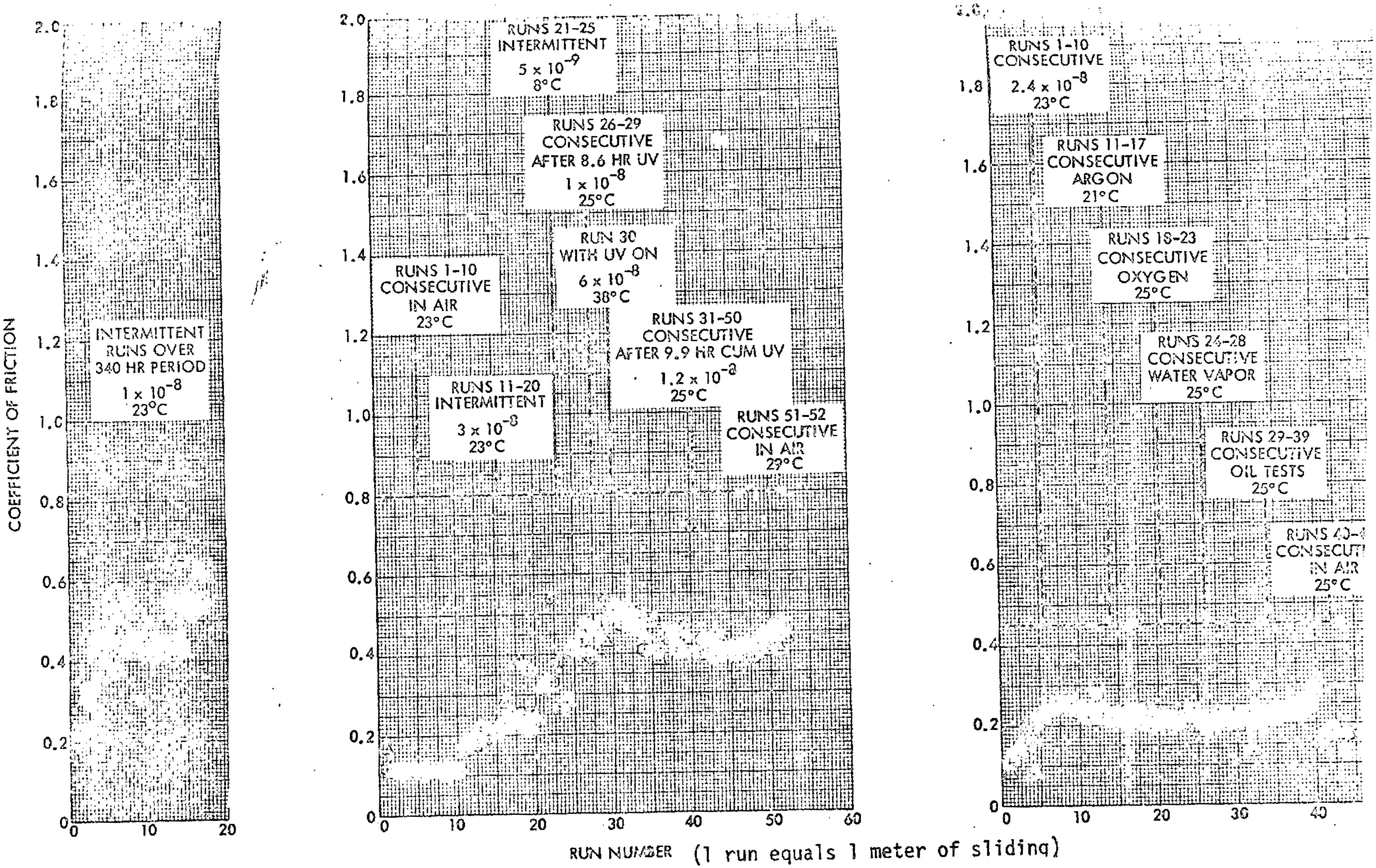


PRELAUNCH
GROUND TESTS
IN VACUUM

POST LAUNCH
GROUND TESTS
IN VACUUM

POST LAUNCH
GROUND TESTS
IN CONTROLLED ENVIRONMENT

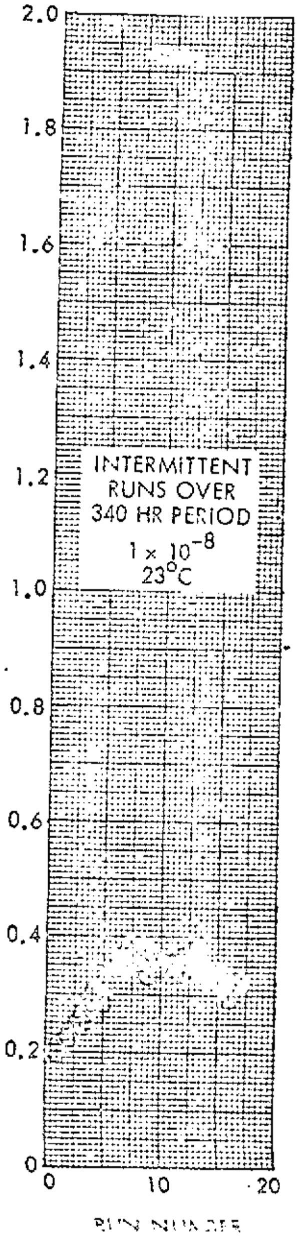
2.0


COEFFICIENT OF FRICTION
INTERMITTENT RUNS OVER 340 HR PERIOD
1 x 10^-8
23°C
RUNS 21-25 INTERMITTENT
5 x 10^-9
8°C
RUNS 26-29 CONSECUTIVE AFTER 8.6 HR UV
1 x 10^-8
25°C
RUN 30 WITH UV ON
6 x 10^-8
38°C
RUNS 1-10 CONSECUTIVE IN AIR
23°C
RUNS 31-50 CONSECUTIVE AFTER 9.9 HR CUM UV
1.2 x 10^-8
25°C
RUNS 11-20 INTERMITTENT
3 x 10^-8
23°C
RUNS 51-52 CONSECUTIVE IN AIR
29°C
RUNS 1-10 CONSECUTIVE
2.4 x 10^-8
23°C
RUNS 11-17 CONSECUTIVE ARGON
21°C
RUNS 18-23 CONSECUTIVE OXYGEN
25°C
RUNS 24-28 CONSECUTIVE WATER VAPOR
25°C
RUNS 29-39 CONSECUTIVE OIL TESTS
25°C
IN AIR
25°C
RUN NUMBER (1 run equals 1 meter of sliding)

PRELAUNCH GROUND TESTS IN VACUUM

POST LAUNCH GROUND TESTS IN VACUUM

POST LAUNCH GROUND TESTS IN CONTROLLED ENVIRONMENT



NO DATA AVAILABLE FROM POST LAUNCH GROUND TESTS

20256-6001-R0-00

TUNGSTEN CARBIDE X GOLD

○ CYCLE 7
△ CYCLE 15

○ CYCLE 7
△ CYCLE 15

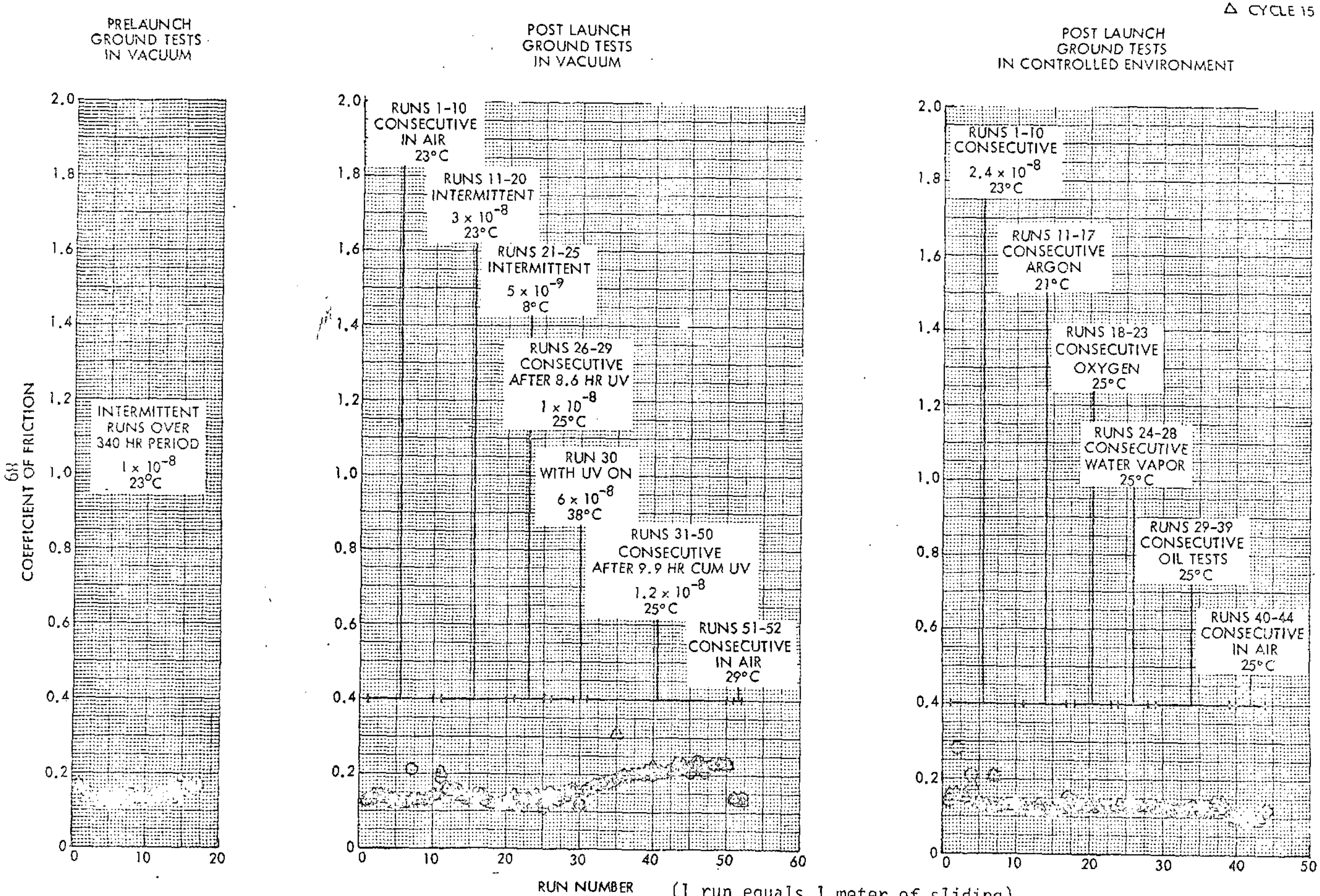
PRELAUNCH GROUND TESTS

POST LAUNCH GROUND TESTS IN VACUUM

POST LAUNCH GROUND TESTS IN CONTROLLED ENVIRONMENT

TUNGSTEN CARBIDE X GOLD

△ CYCLE 15

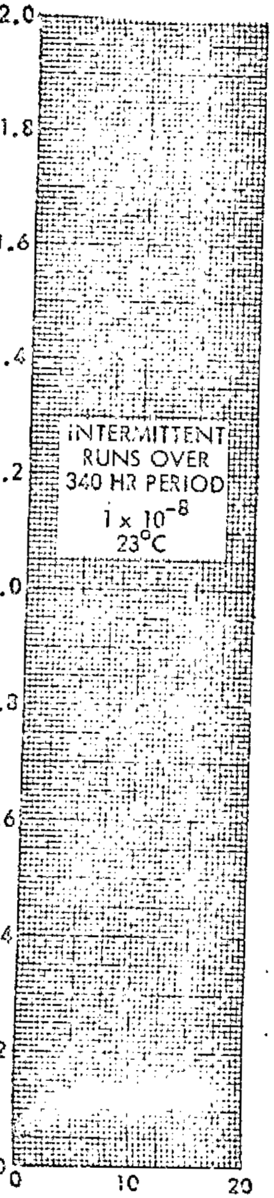


(1 run equals 1 meter of sliding)

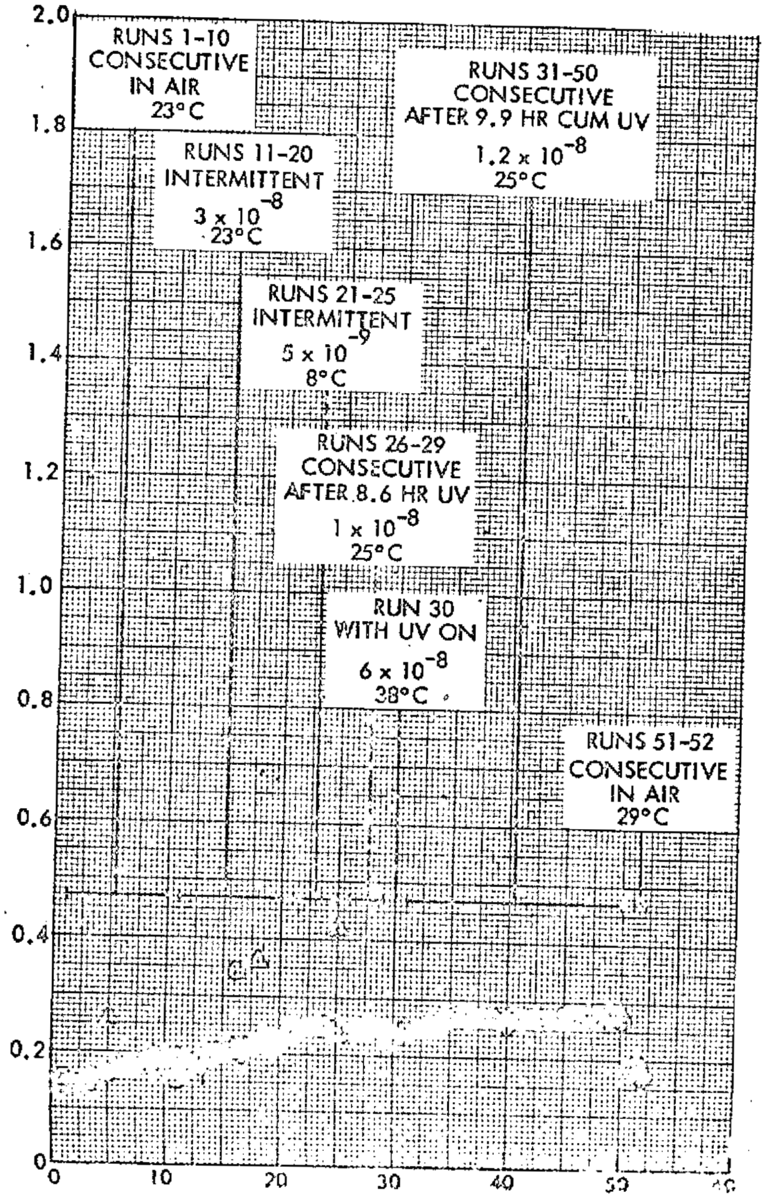
20256-6001-R0-00

Δ CYCLE 16

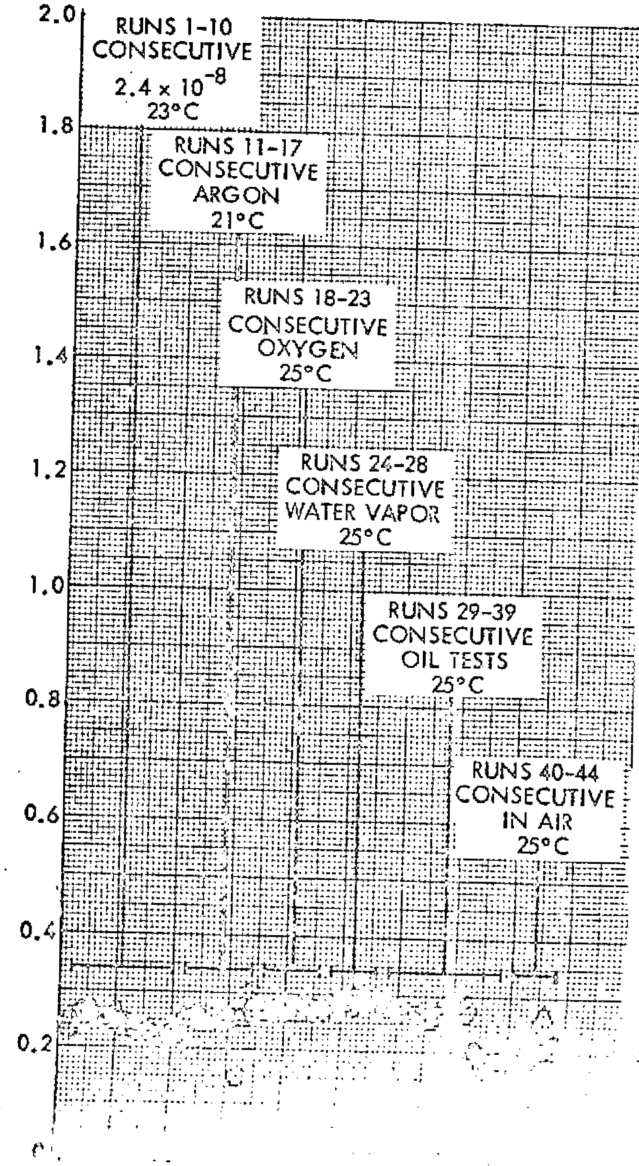
PRELAUNCH
GROUND TESTS
IN VACUUM



POST LAUNCH
GROUND TESTS
IN VACUUM



POST LAUNCH
GROUND TESTS
IN CONTROLLED ENVIRONMENT



20256-6001-R

440C STAINLESS STEEL X TUNGSTEN ...

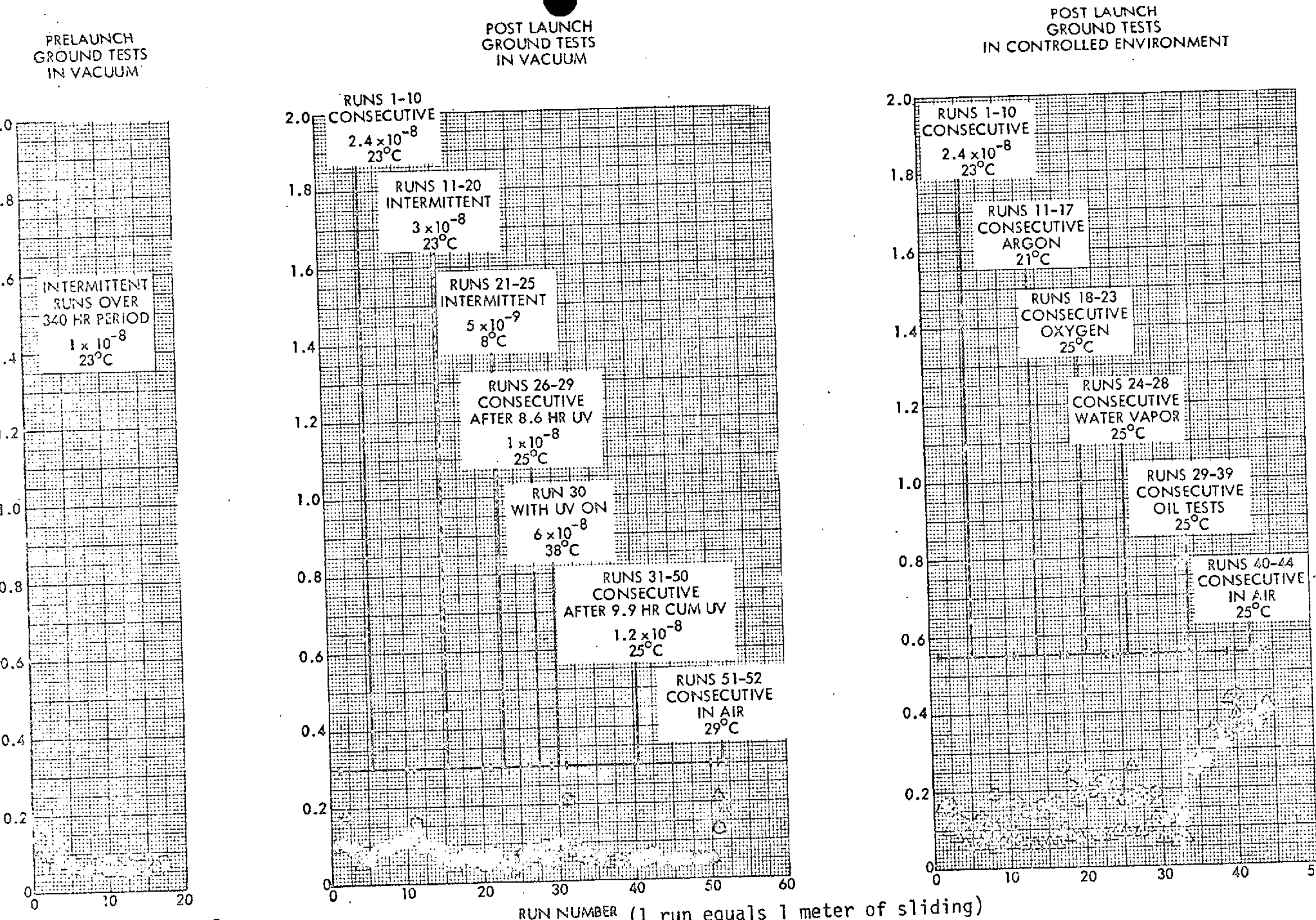
PRELAUNCH
GROUND TESTS

POST LAUNCH
GROUND TESTS
IN VACUUM

POST LAUNCH
GROUND TESTS
IN CONTROLLED ENVIRONMENT

2.0

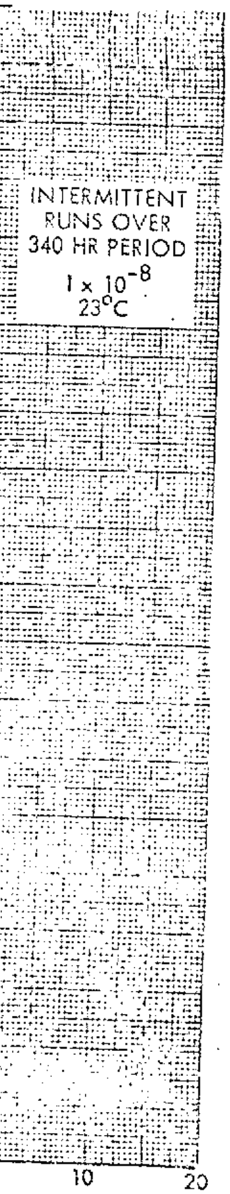
440C STAINLESS STEEL X TUNGSTEN ...



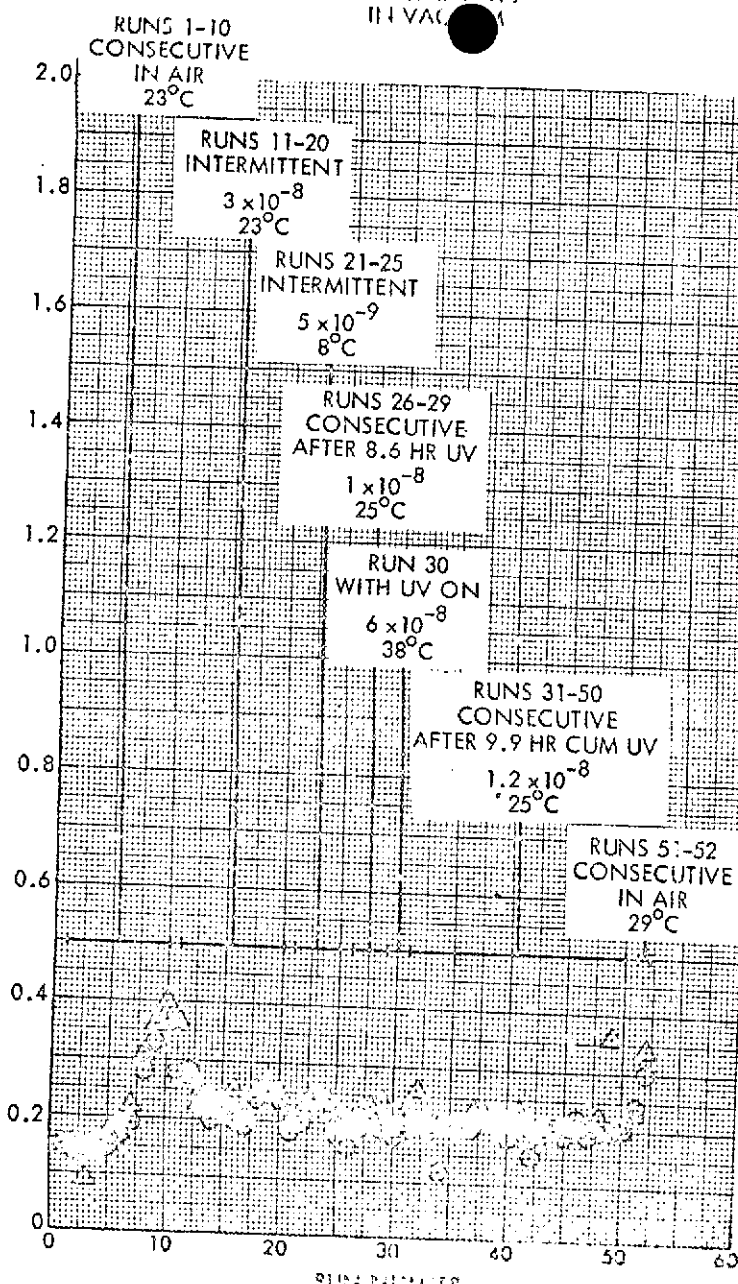
20256-6001-R0-00

POST LAUNCH
GROUND TESTS
IN VAC[illegible]M

POST LAUNCH
GROUND TESTS
IN CONTROLLED ENVIRONMENT



PRELAUNCH
GROUND TESTS
IN VACUUM



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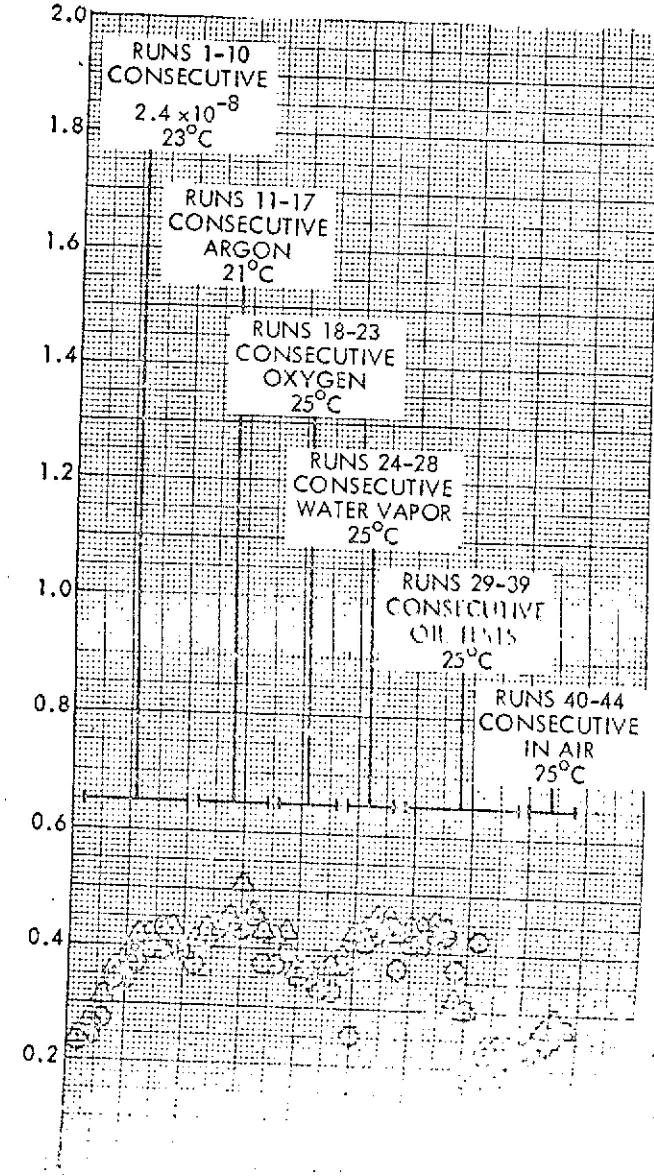
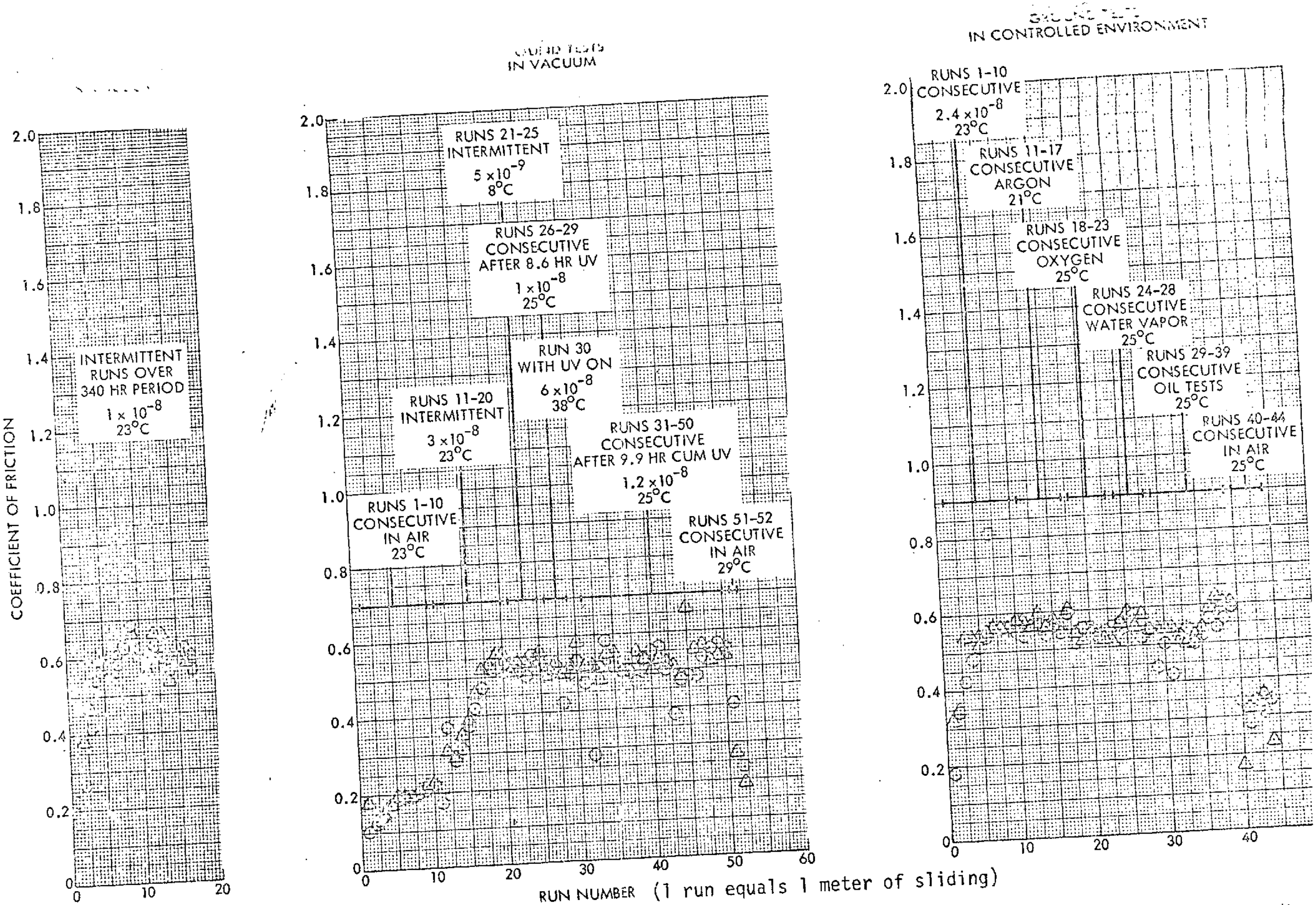
POST LAUNCH
GROUND TESTS
IN VACUUM



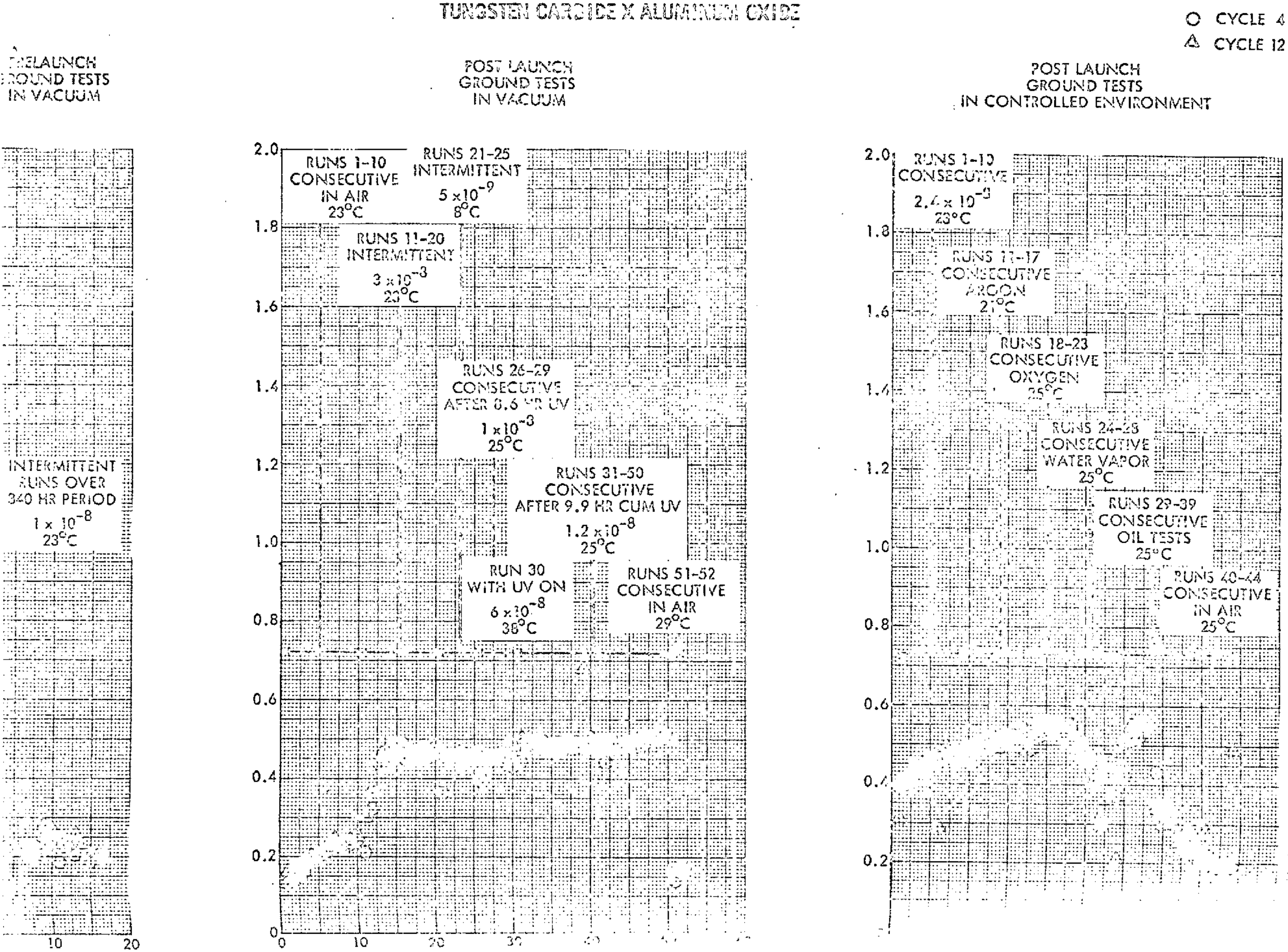
20256-6001

GROUND TESTS
IN CONTROLLED ENVIRONMENT



IN VACUUM
IN CONTROLLED ENVIRONMENT
COEFFICIENT OF FRICTION
INTERMITTENT RUNS OVER 340 HR PERIOD
1 × 10^-8
23°C
RUNS 1-10 CONSECUTIVE IN AIR
23°C
RUNS 11-20 INTERMITTENT
3 × 10^-8
23°C
RUNS 21-25 INTERMITTENT
5 × 10^-9
8°C
RUNS 26-29 CONSECUTIVE AFTER 8.6 HR UV
1 × 10^-8
25°C
RUN 30 WITH UV ON
6 × 10^-8
38°C
RUNS 31-50 CONSECUTIVE AFTER 9.9 HR CUM UV
1.2 × 10^-8
25°C
RUNS 51-52 CONSECUTIVE IN AIR
29°C
RUNS 1-10 CONSECUTIVE
2.4 × 10^-8
23°C
RUNS 11-17 CONSECUTIVE ARGON
21°C
RUNS 18-23 CONSECUTIVE OXYGEN
25°C
RUNS 24-28 CONSECUTIVE WATER VAPOR
25°C
RUNS 29-39 CONSECUTIVE OIL TESTS
25°C
RUNS 40-44 CONSECUTIVE IN AIR
25°C
RUN NUMBER (1 run equals 1 meter of sliding)

TUNGSTEN CARBIDE X ALUMINUM OXIDE



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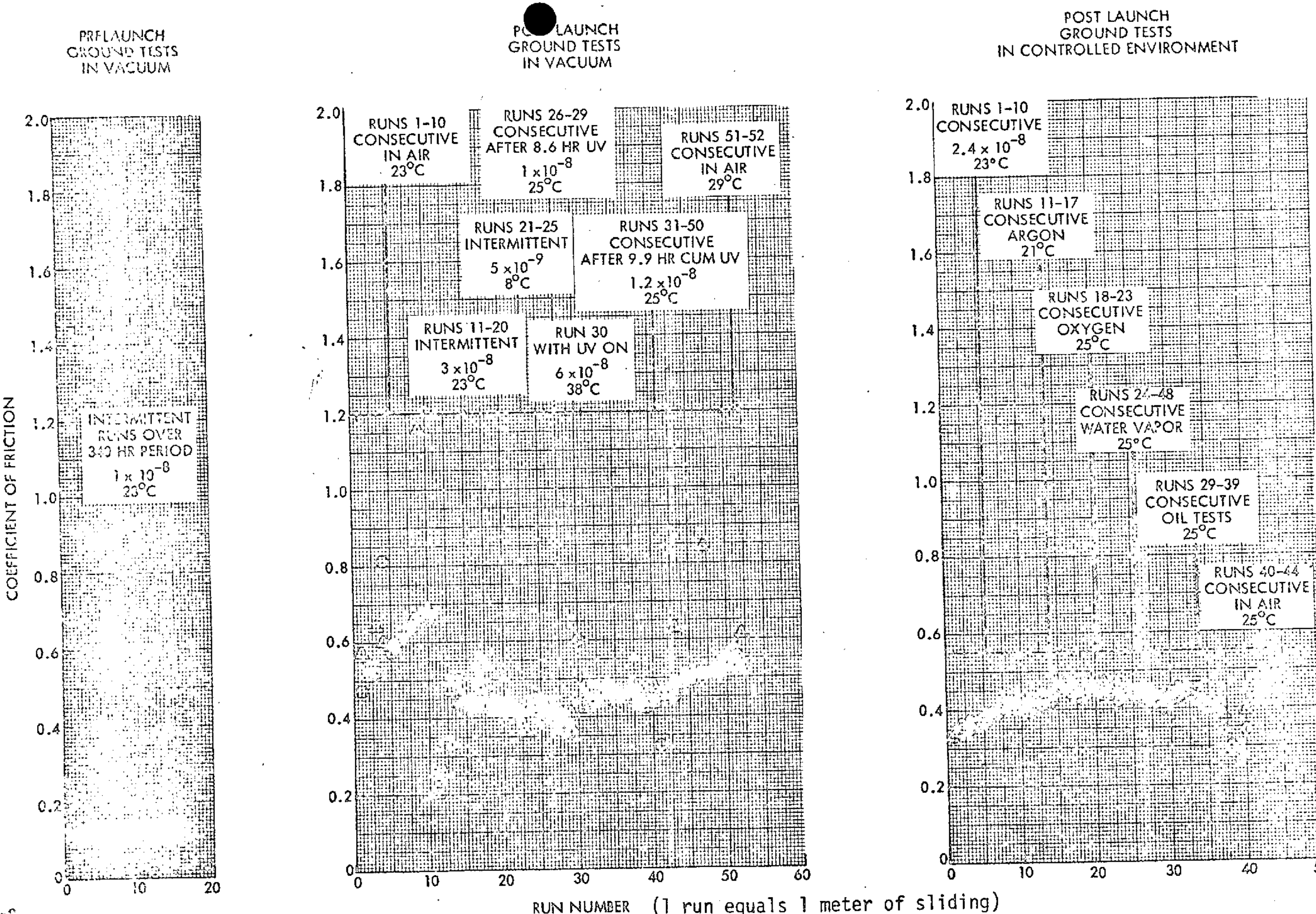
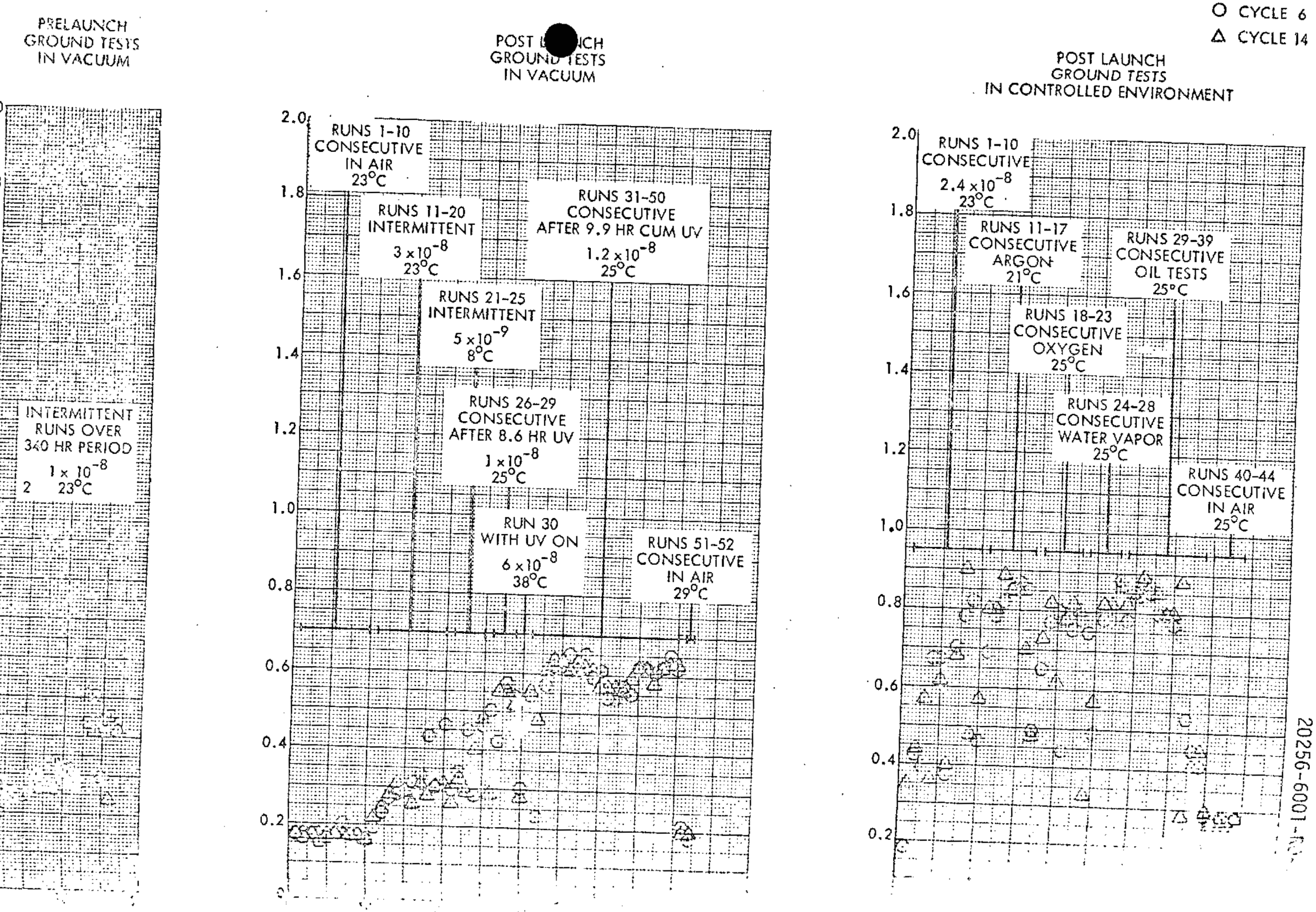
X BERYLLIUM



20256-6001-R0-00

COBALT X TUNGSTEN CARBIDE



96

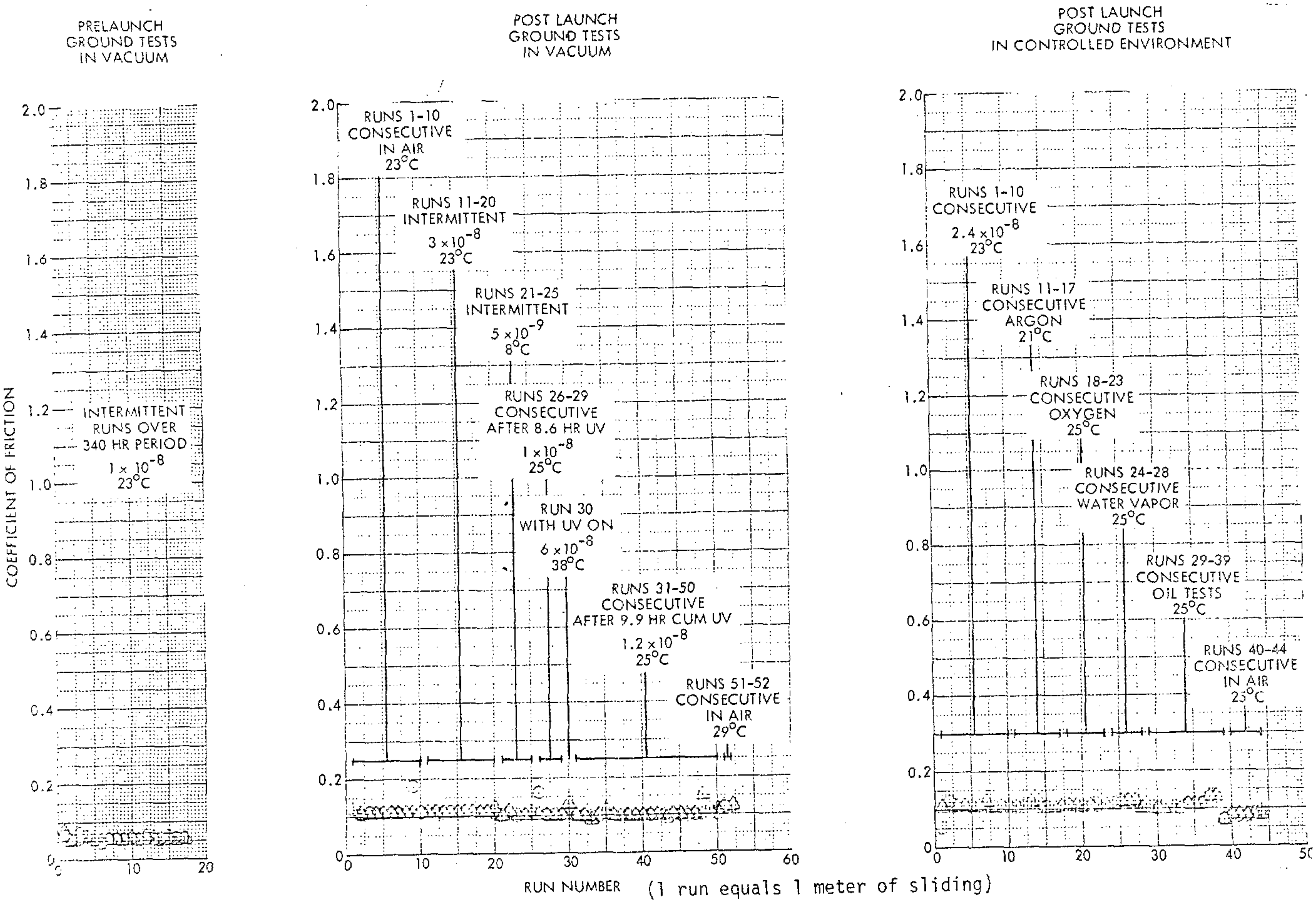
440C STAINLESS STEEL X ...

PRELAUNCH GROUND TESTS IN VACUUM

POST LAUNCH GROUND TESTS IN VACUUM

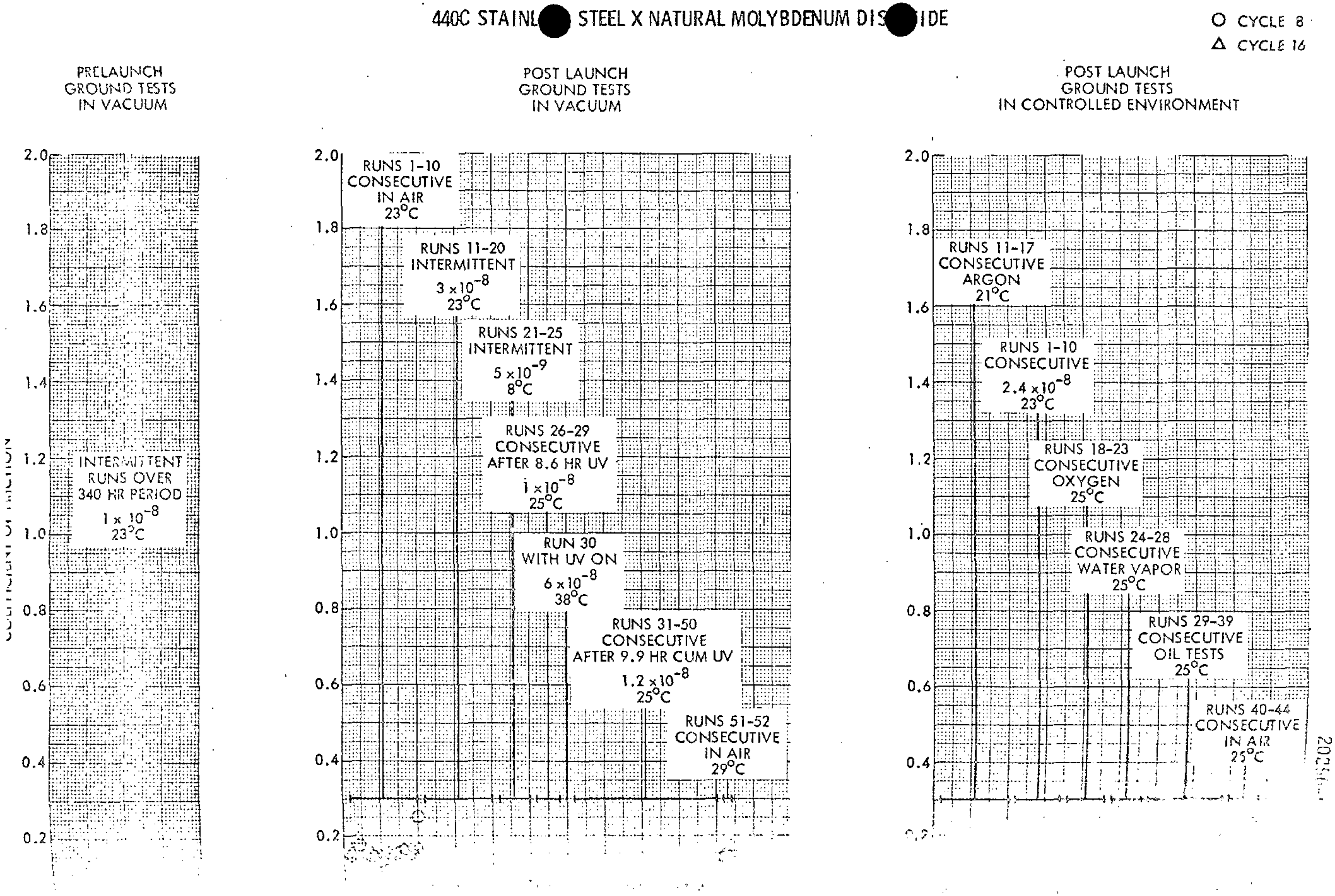
POST LAUNCH GROUND TESTS IN CONTROLLED ENVIRONMENT

△ CYCLE 15



PRELAUNCH GROUND TESTS IN VACUUM
POST LAUNCH GROUND TESTS IN VACUUM
POST LAUNCH GROUND TESTS IN CONTROLLED ENVIRONMENT
COEFFICIENT OF FRICTION
INTERMITTENT RUNS OVER 340 HR PERIOD 1 × 10^-8 23°C
RUNS 1-10 CONSECUTIVE IN AIR 23°C
RUNS 11-20 INTERMITTENT 3 × 10^-8 23°C
RUNS 21-25 INTERMITTENT 5 × 10^-9 8°C
RUNS 26-29 CONSECUTIVE AFTER 8.6 HR UV 1 × 10^-8 25°C
RUN 30 WITH UV ON 6 × 10^-8 38°C
RUNS 31-50 CONSECUTIVE AFTER 9.9 HR CUM UV 1.2 × 10^-8 25°C
RUNS 51-52 CONSECUTIVE IN AIR 29°C
RUNS 1-10 CONSECUTIVE 2.4 × 10^-8 23°C
RUNS 11-17 CONSECUTIVE ARGON 21°C
RUNS 18-23 CONSECUTIVE OXYGEN 25°C
RUNS 24-28 CONSECUTIVE WATER VAPOR 25°C
RUNS 29-39 CONSECUTIVE OIL TESTS 25°C
RUNS 40-44 CONSECUTIVE IN AIR 25°C
RUN NUMBER (1 run equals 1 meter of sliding)

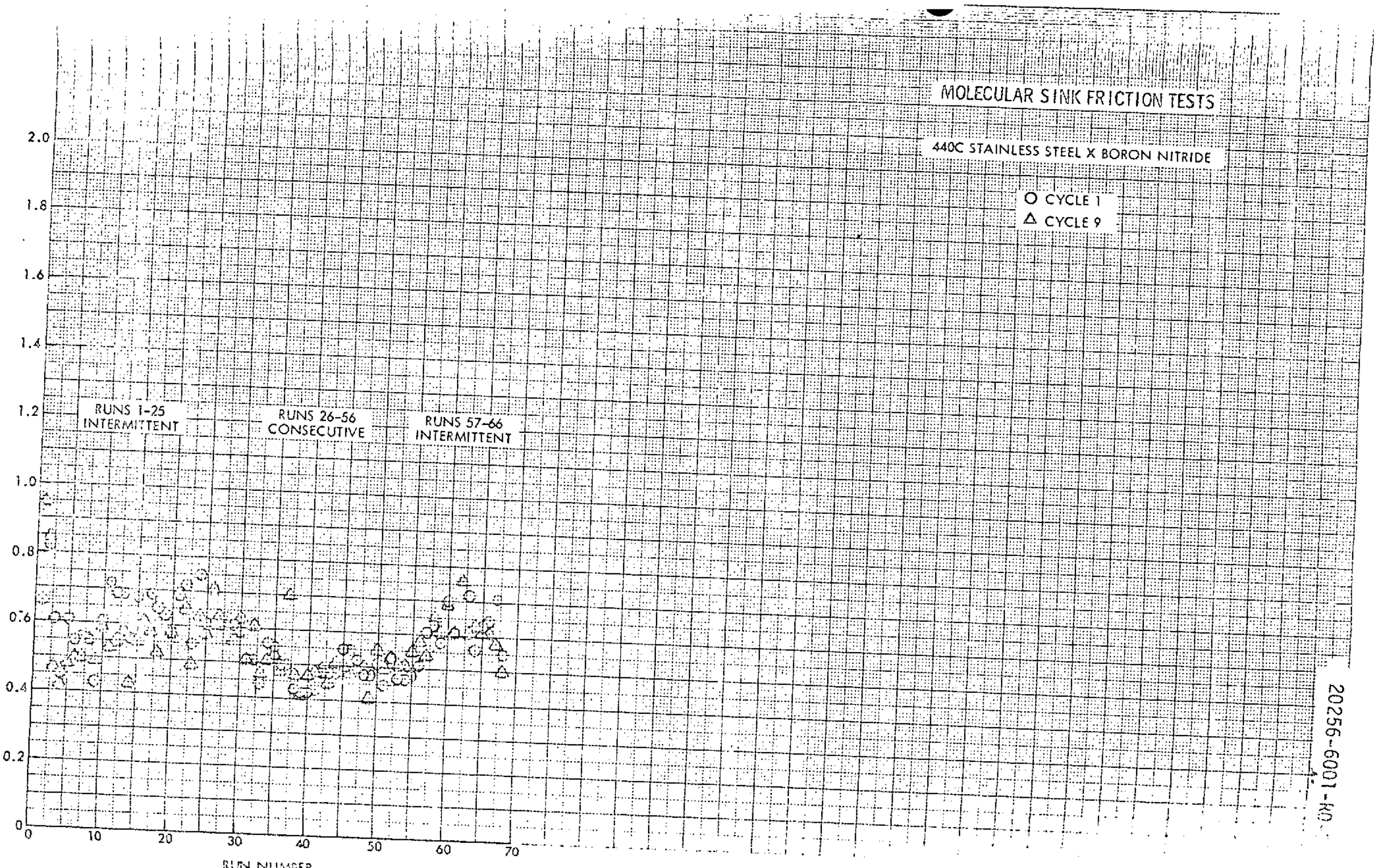
440C STAINL STEEL X NATURAL MOLYBDENUM DIS IDE



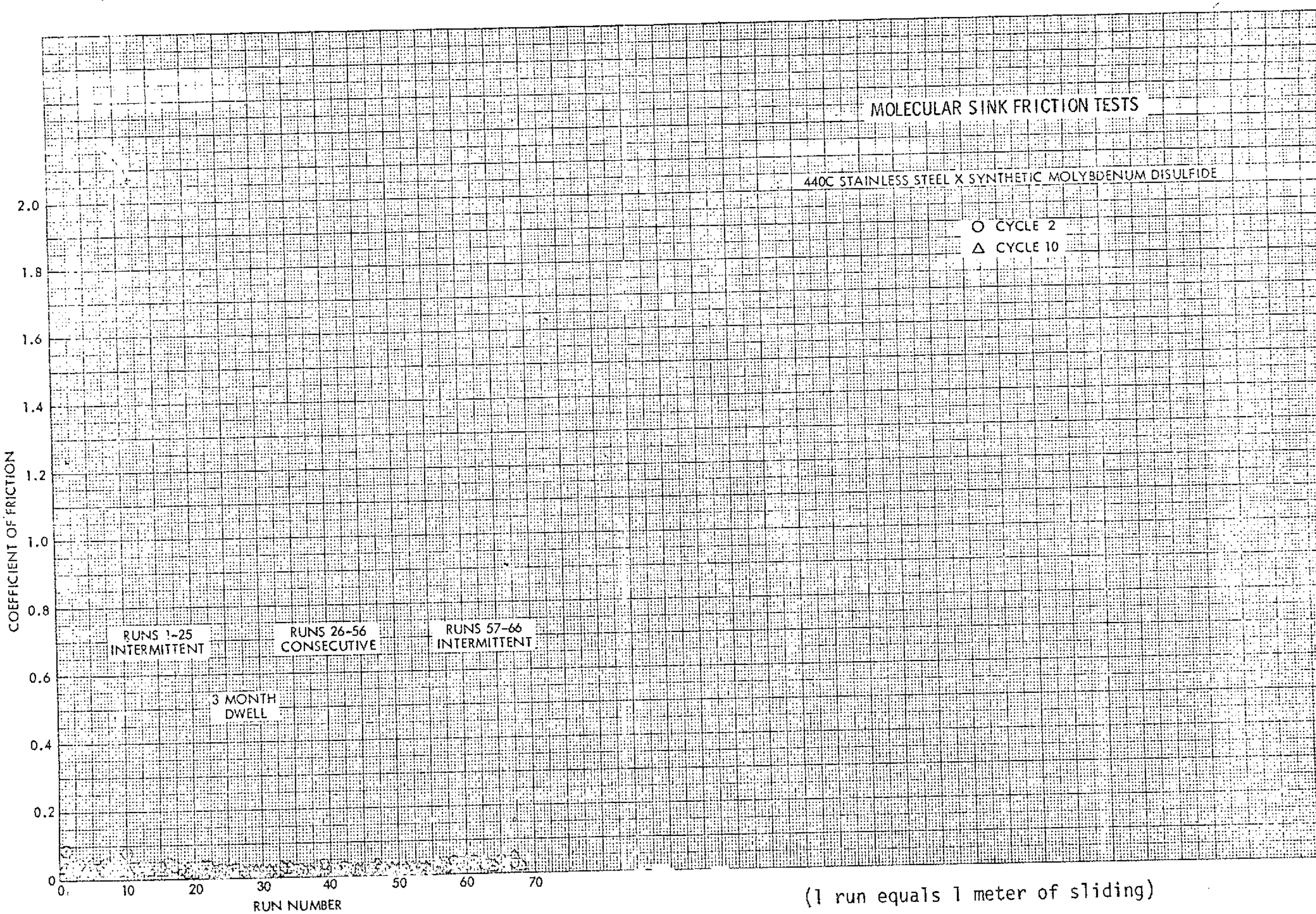
APPENDIX C
MOLECULAR SINK FRICTION DATA

This section contains the graphical presentations of the friction data for the sixteen material combinations studied in the Molecular Sink Vacuum Test Program.

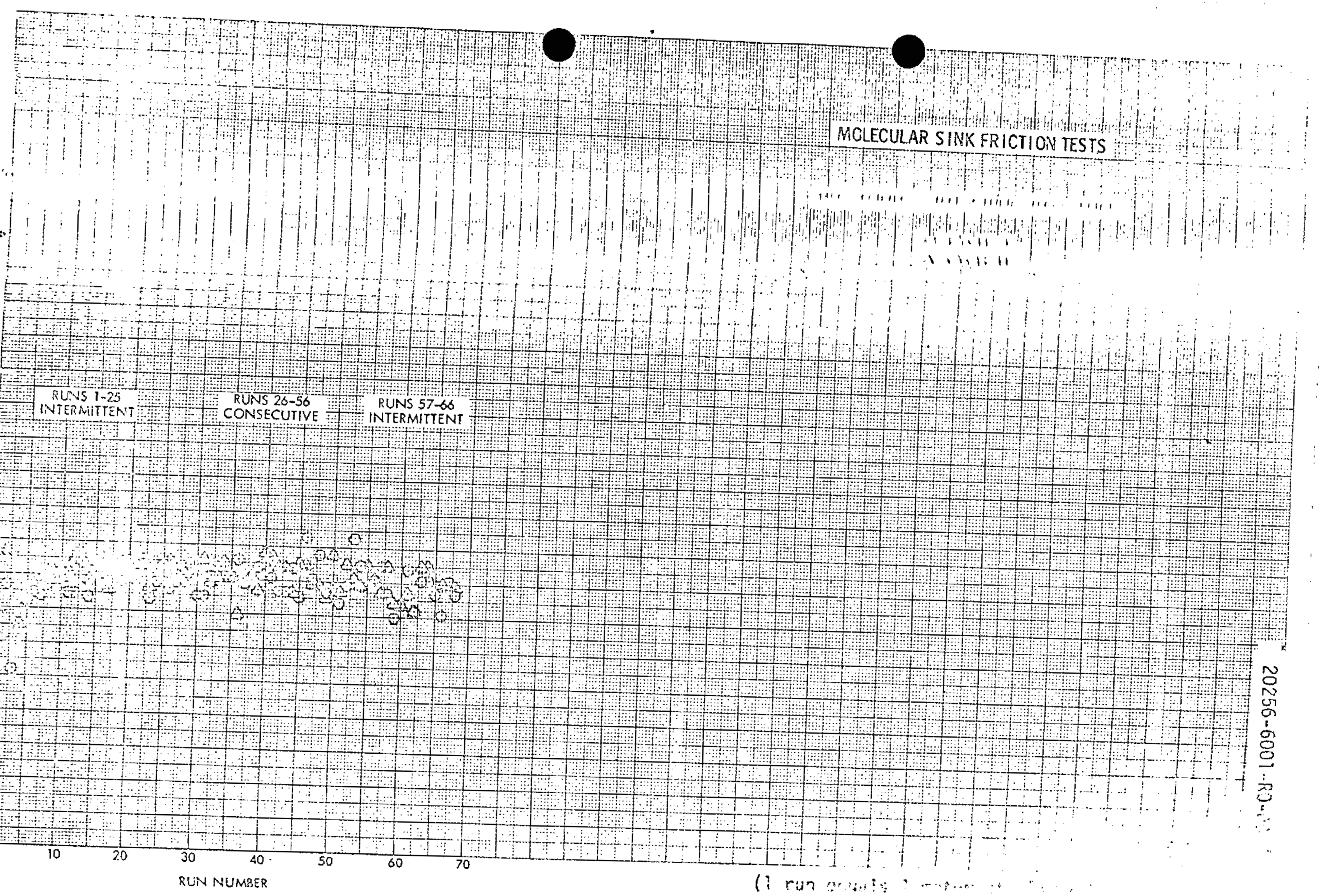
The order of presentation is by the experiment designations on the modules A1-8 and B1-8.

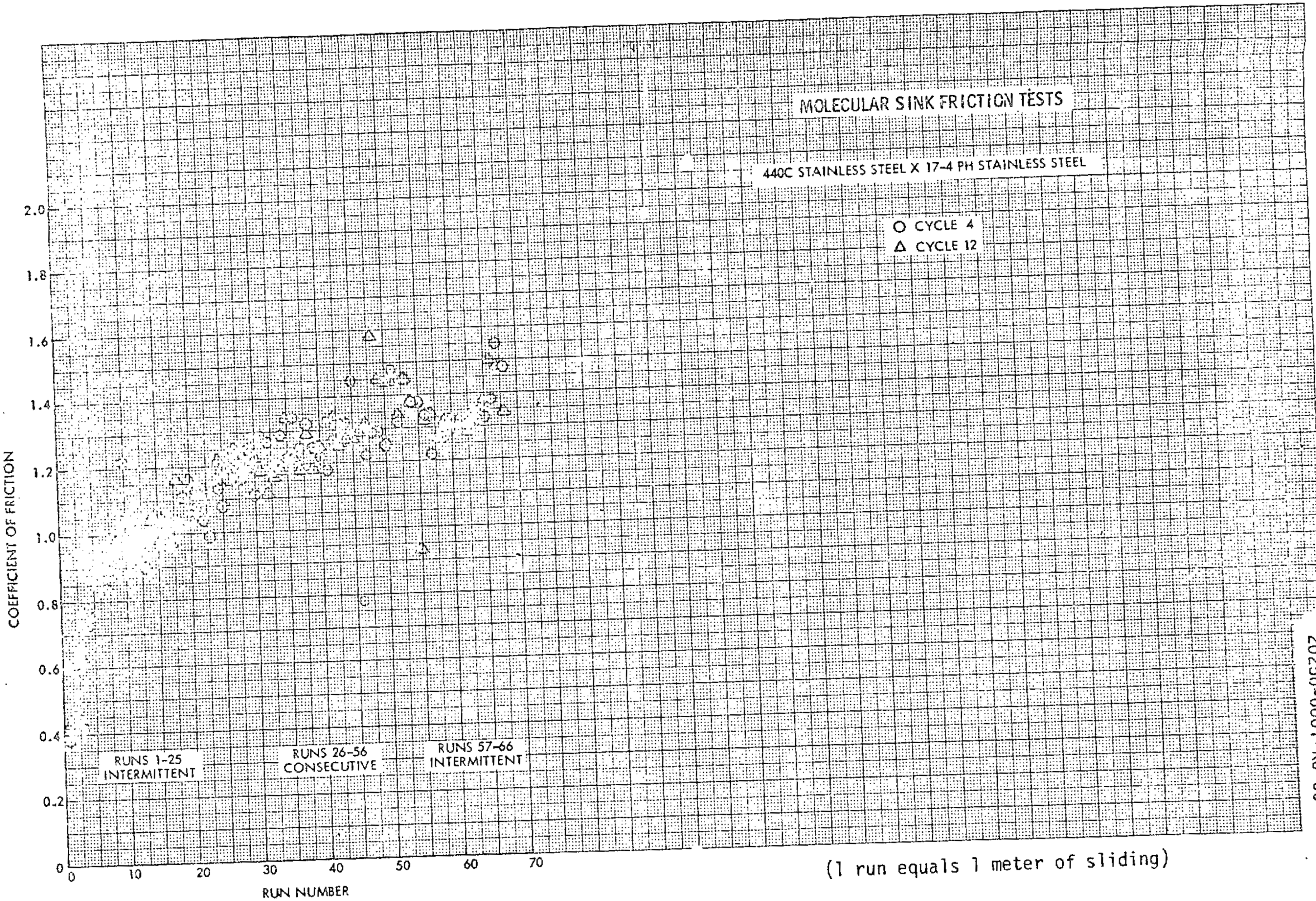


MOLECULAR SINK FRICTION TESTS
440C STAINLESS STEEL X BORON NITRIDE
O CYCLE 1
Δ CYCLE 9
RUNS 1-25
INTERMITTENT
RUNS 26-56
CONSECUTIVE
RUNS 57-66
INTERMITTENT
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
RUN NUMBER
20256-6001-R0



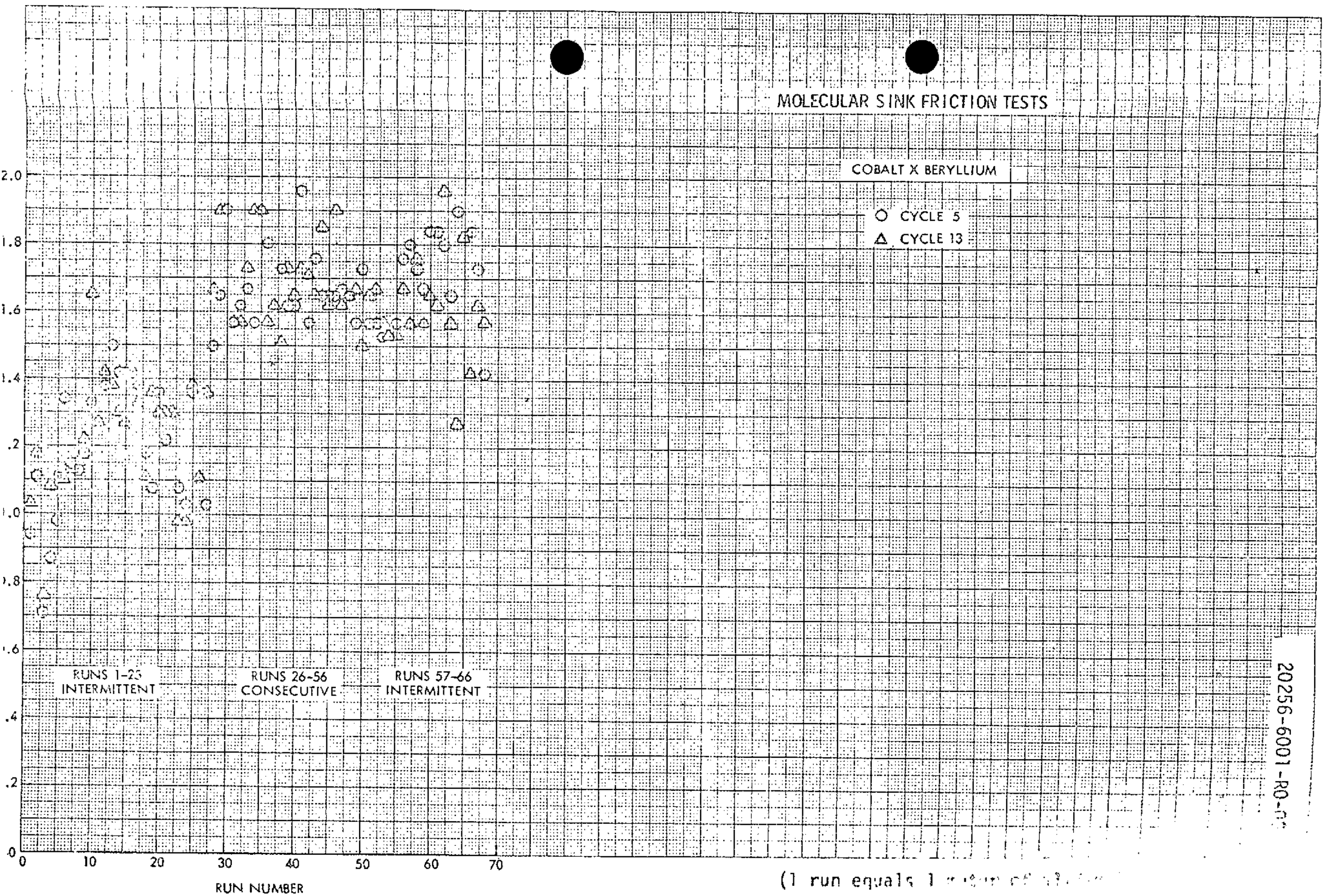
(1 run equals 1 meter of sliding)


MOLECULAR SINK FRICTION TESTS
RUNS 1-25
INTERMITTENT
RUNS 26-56
CONSECUTIVE
RUNS 57-66
INTERMITTENT
10
20
30
40
50
60
70
RUN NUMBER
20256-6001-RO-



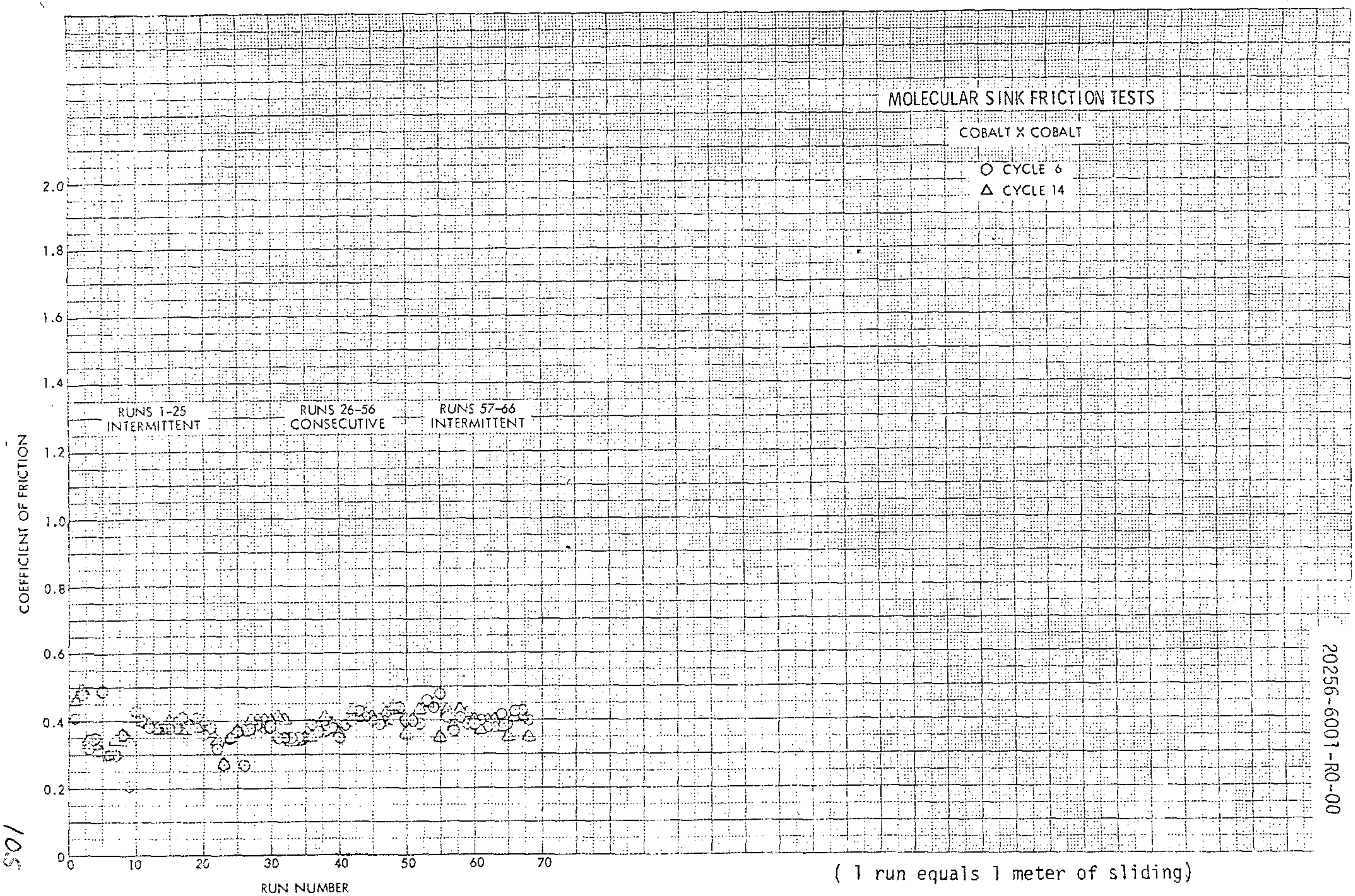
(1 run equals 1 meter of sliding)

20256-6001-R0-00



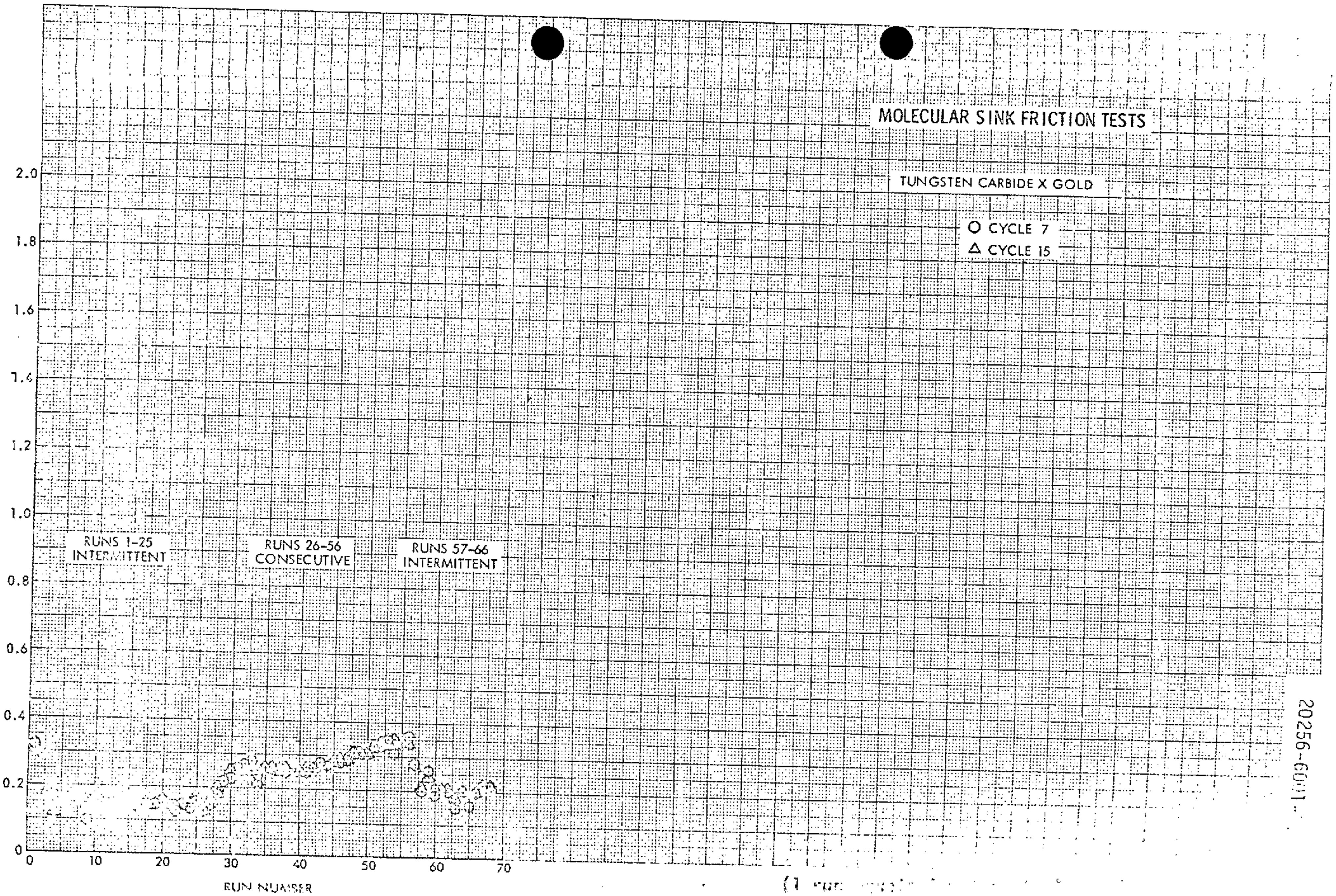
(1 run equals 1

20256-6001-R0-

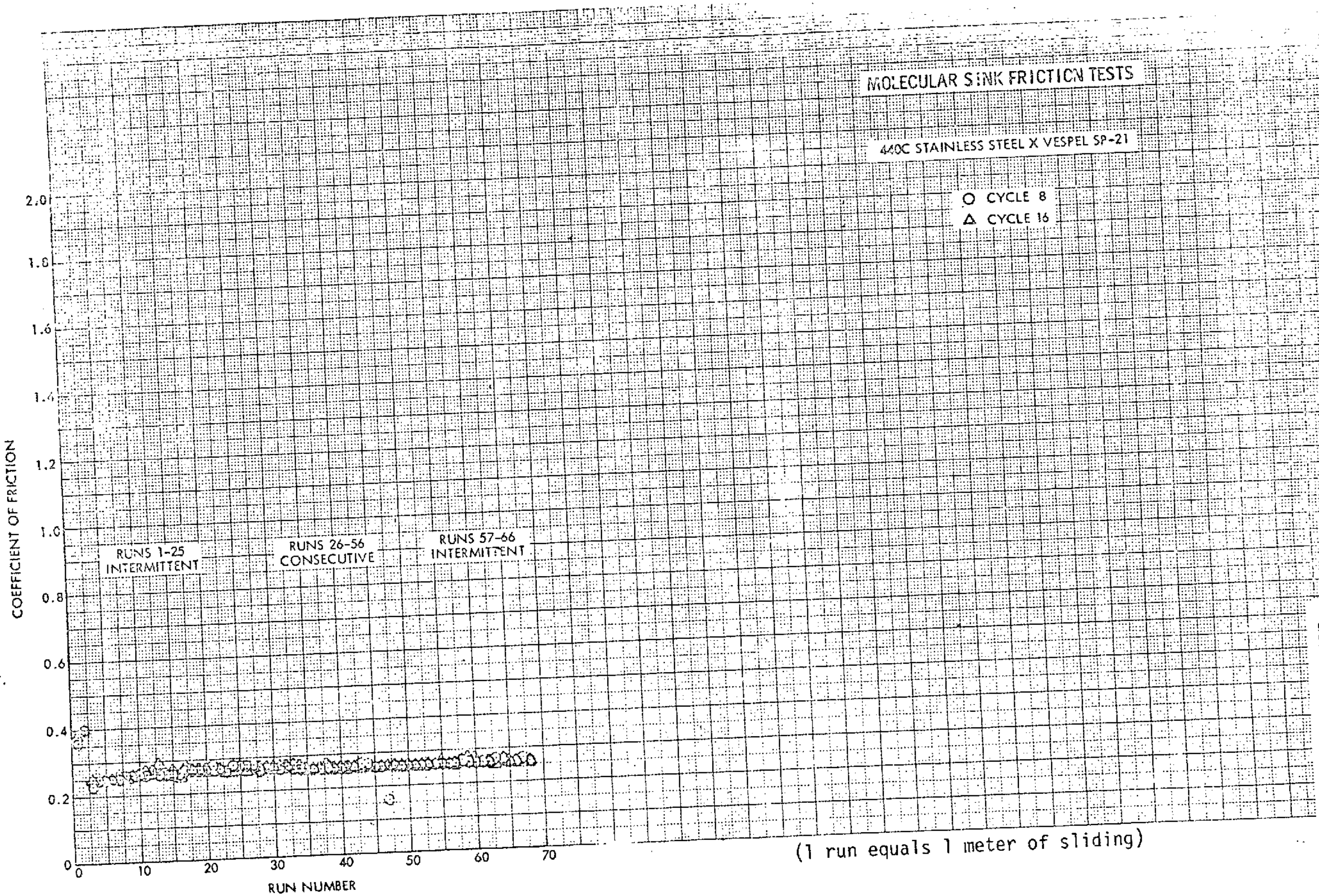


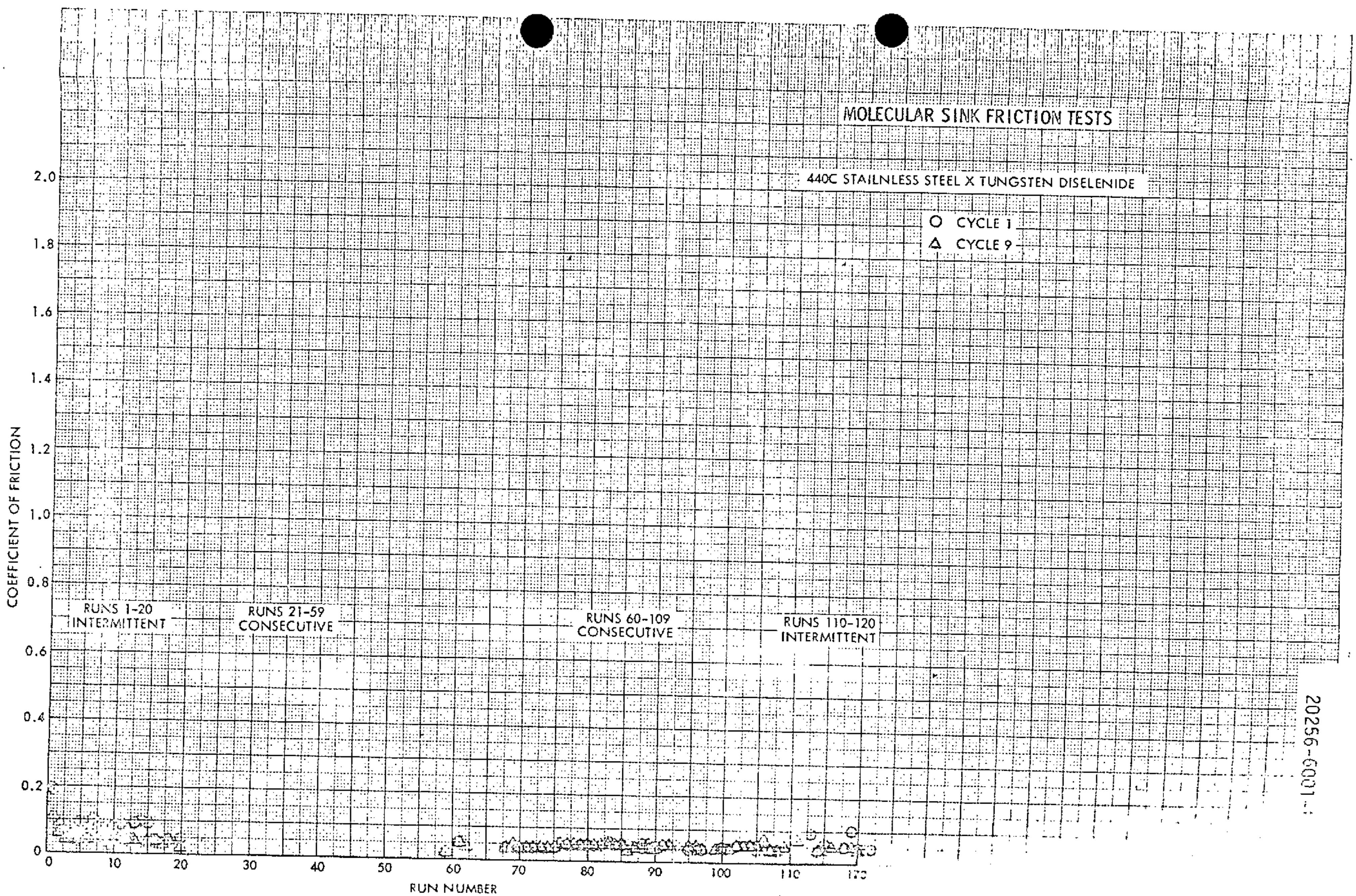
(1 run equals 1 meter of sliding)

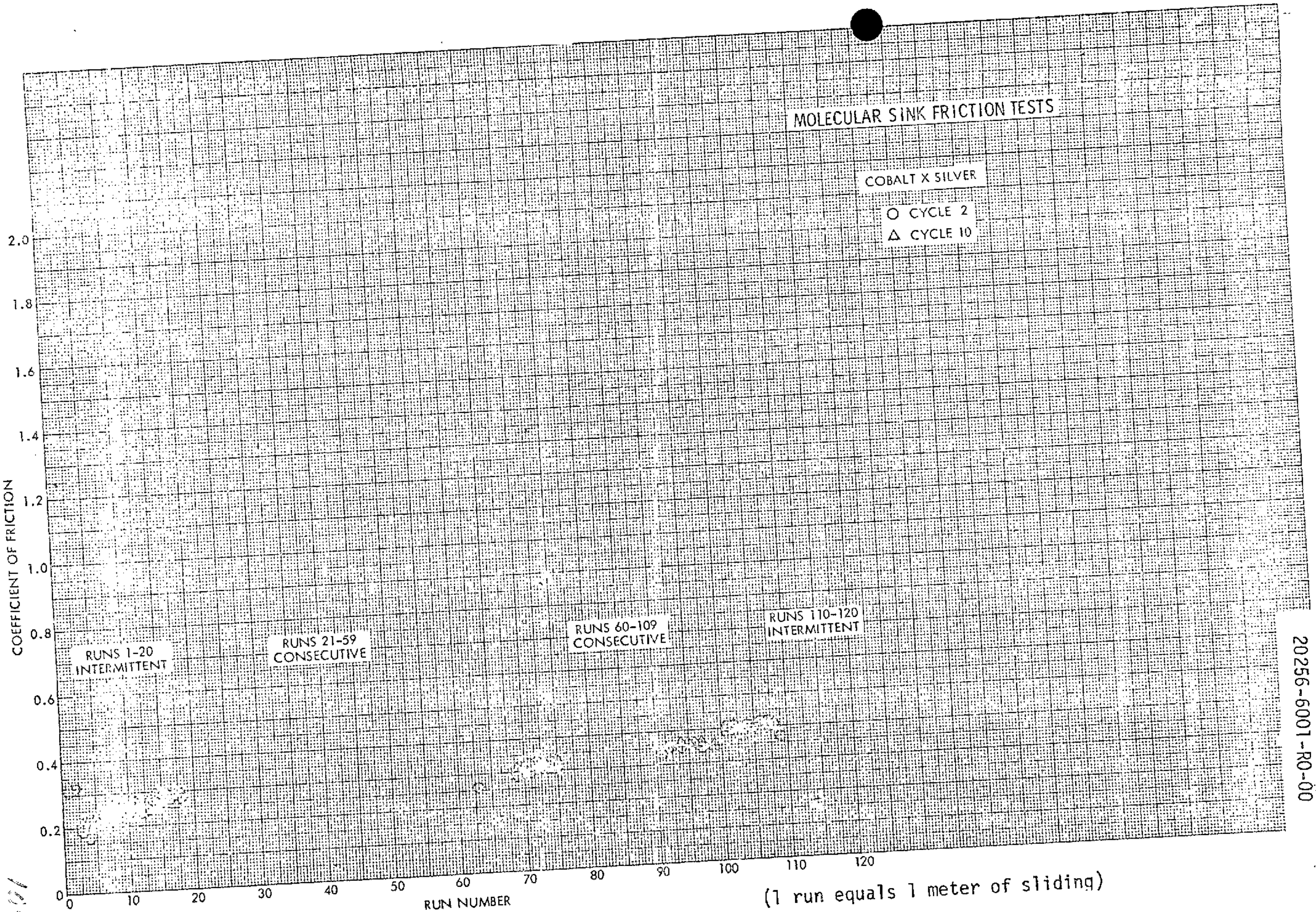
20256-6001-R0-00


MOLECULAR SINK FRICTION TESTS
TUNGSTEN CARBIDE X GOLD
O CYCLE 7
Δ CYCLE 15
RUNS 1-25 INTERMITTENT
RUNS 26-56 CONSECUTIVE
RUNS 57-66 INTERMITTENT
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
RUN NUMBER
20256-6001

106


MOLECULAR SINK FRICTION TESTS
440C STAINLESS STEEL X VESPEL SP-21
○ CYCLE 8
△ CYCLE 16
RUNS 1-25
INTERMITTENT
RUNS 26-56
CONSECUTIVE
RUNS 57-66
INTERMITTENT
COEFFICIENT OF FRICTION
RUN NUMBER
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
10
20
30
40
50
60
70
(1 run equals 1 meter of sliding)


MOLECULAR SINK FRICTION TESTS
440C STAILNLESS STEEL X TUNGSTEN DISELENIDE
O CYCLE 1
Δ CYCLE 9
RUNS 1-20 INTERMITTENT
RUNS 21-59 CONSECUTIVE
RUNS 60-109 CONSECUTIVE
RUNS 110-120 INTERMITTENT
COEFFICIENT OF FRICTION
RUN NUMBER
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
10
20
30
40
50
60
70
80
90
100
110
120
20256-6001

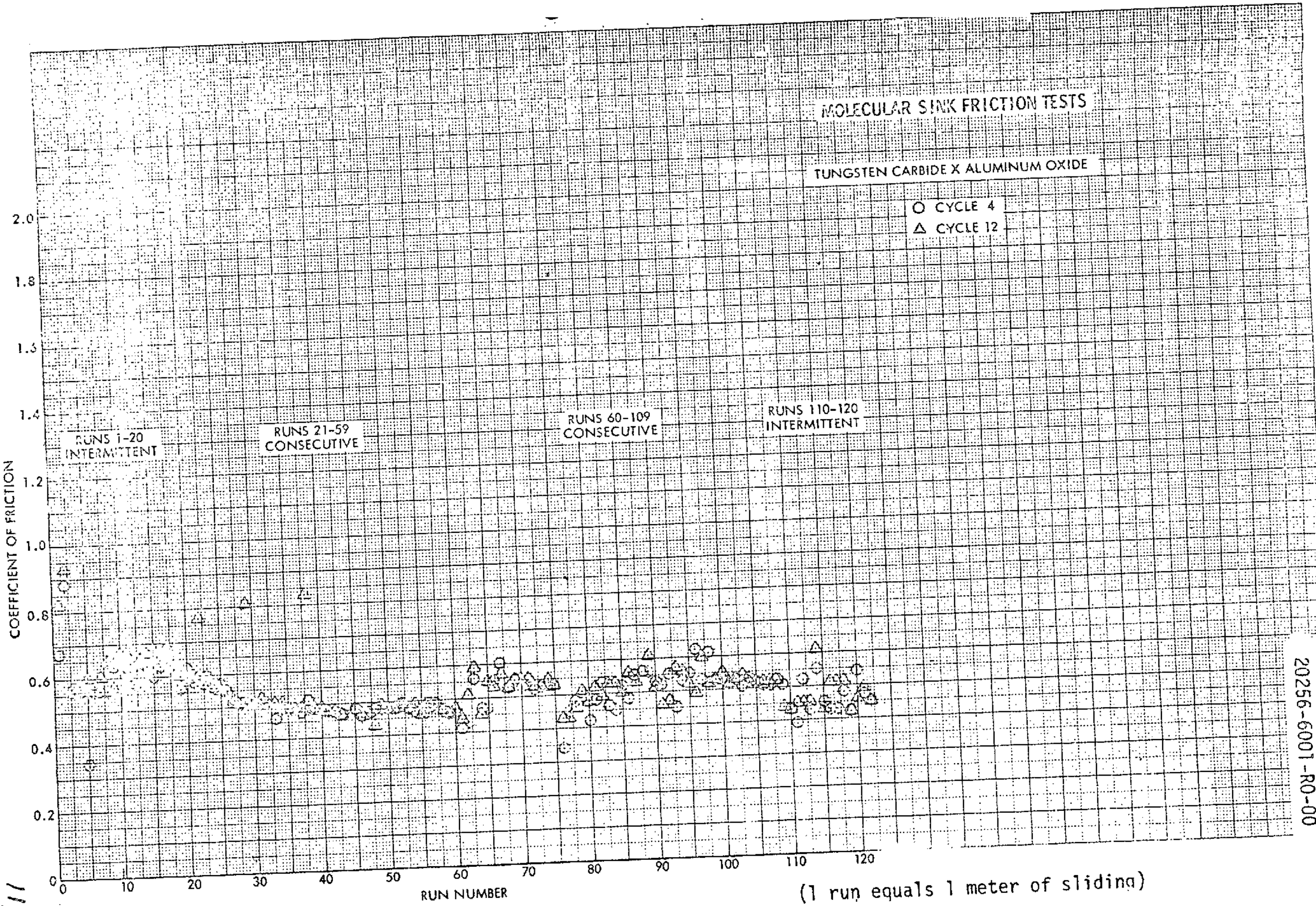


20256-6001-R0-00

TUNGSTEN CARBIDE X TUNGSTEN CARBIDE

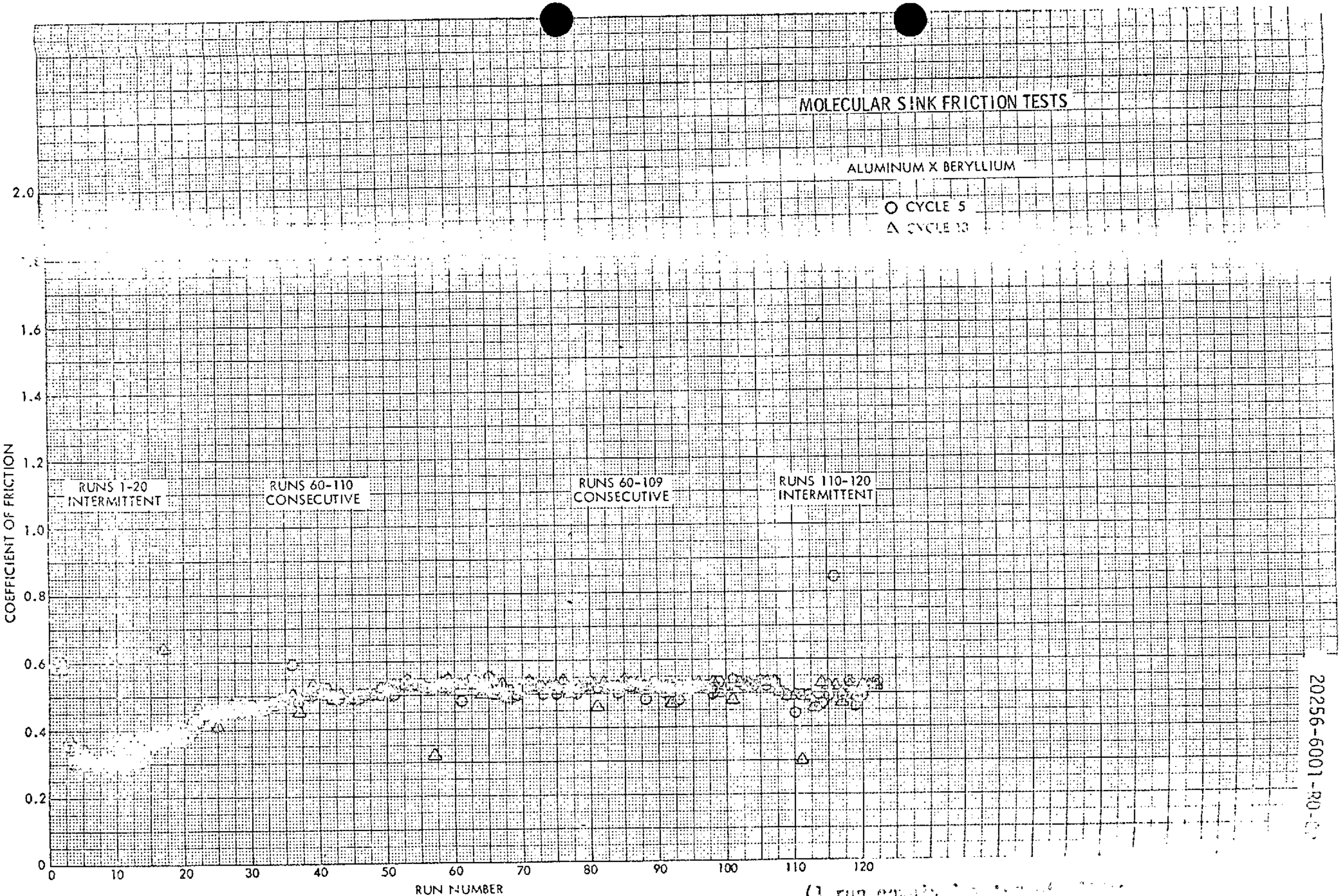
NO MOLECULAR SINK TEST DATA AVAILABLE

20256-6001



(1 run equals 1 meter of sliding)

20256-6001-R0-00



(1 run equals ...

20256-6001-RO-00

112

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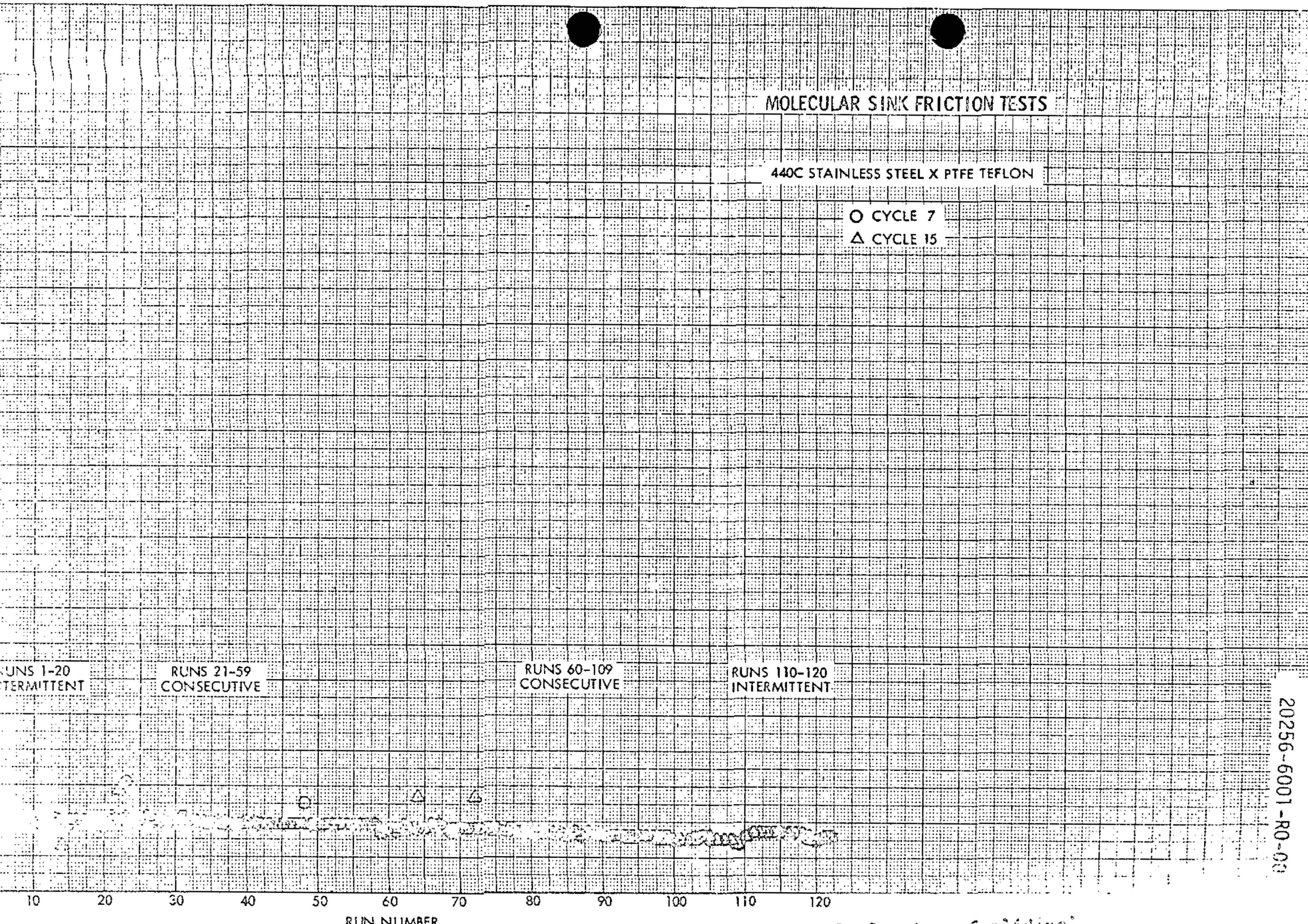
COBALT X TUNGSTEN CARBIDE

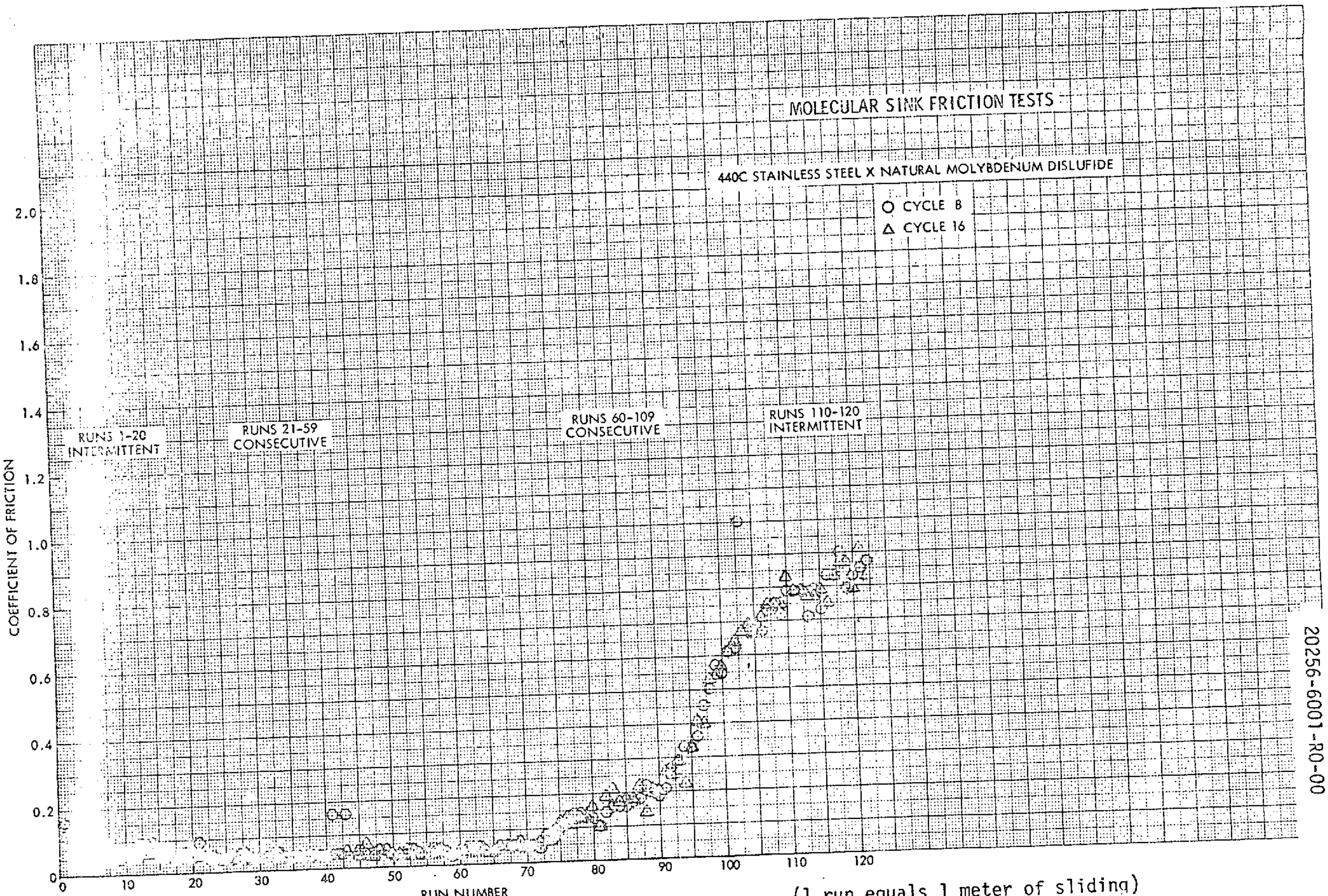
NO MOLECULAR SINK TEST DATA AVAILABLE

20256-6001-R0-00



(1 run equals 1 meter of sliding)

20256-6001-R0-00



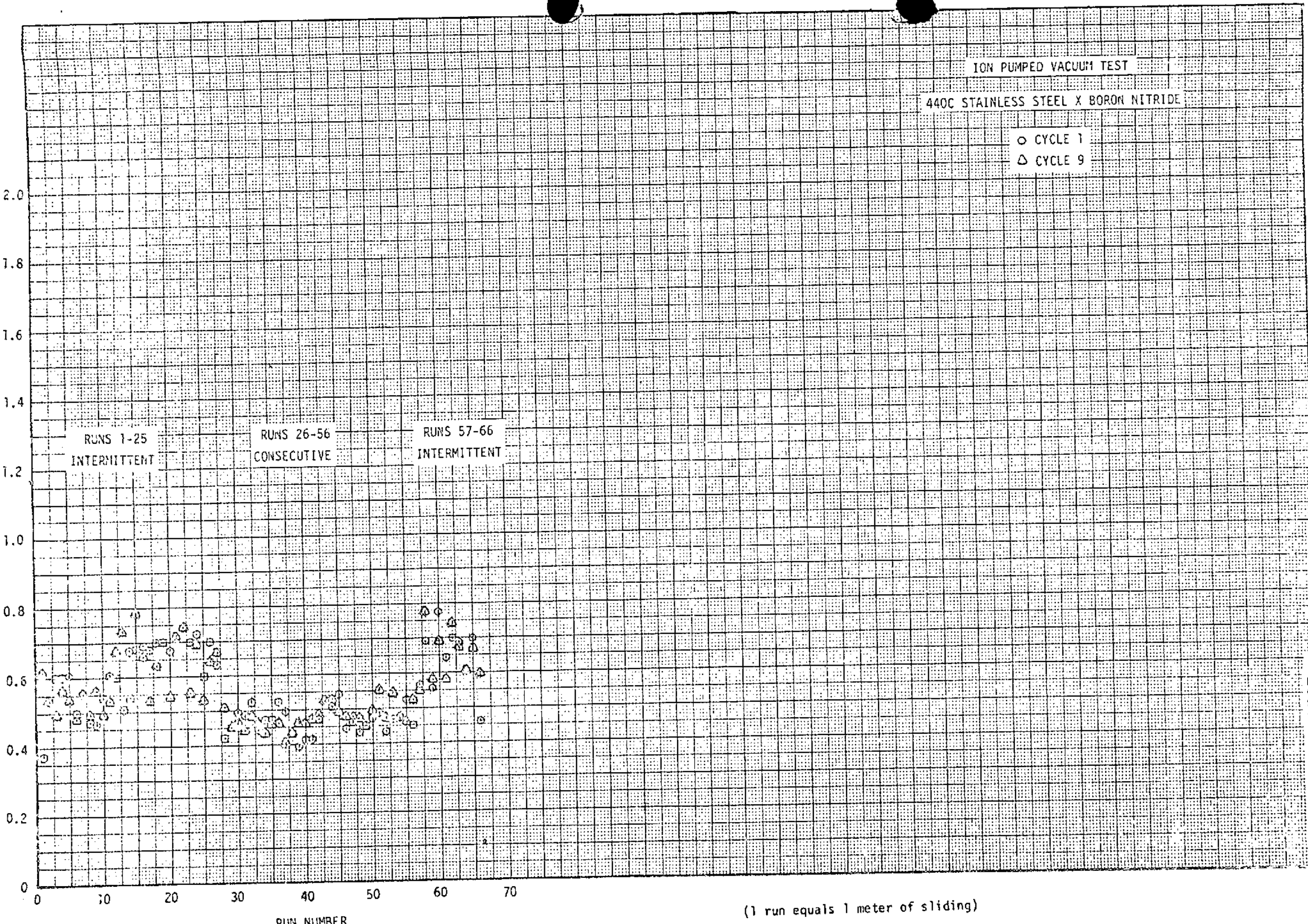
(1 run equals 1 meter of sliding)

20256-6001-R0-00

APPENDIX D
ION PUMPED FRICTION DATA

This section contains the graphs of ground test friction data taken in ion pumped vacuum under contrast F04611-[illegible]-C-0029. The study used the same TRW ion pumped chamber used in the subsequent modified ion vacuum test.

The order of presentation is by designation on the modules A1-8 and B1-8.



20256-6001-R0-00

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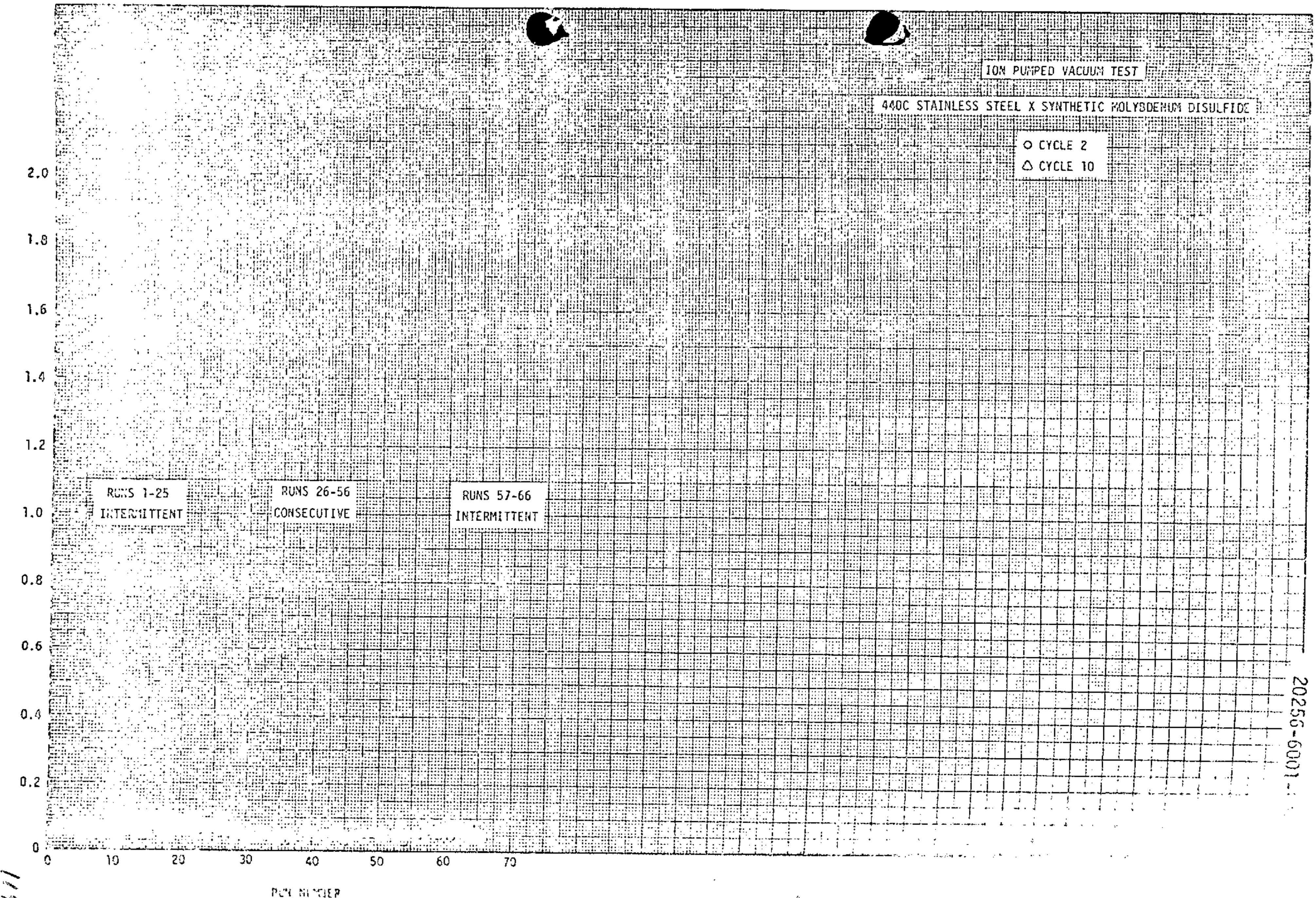
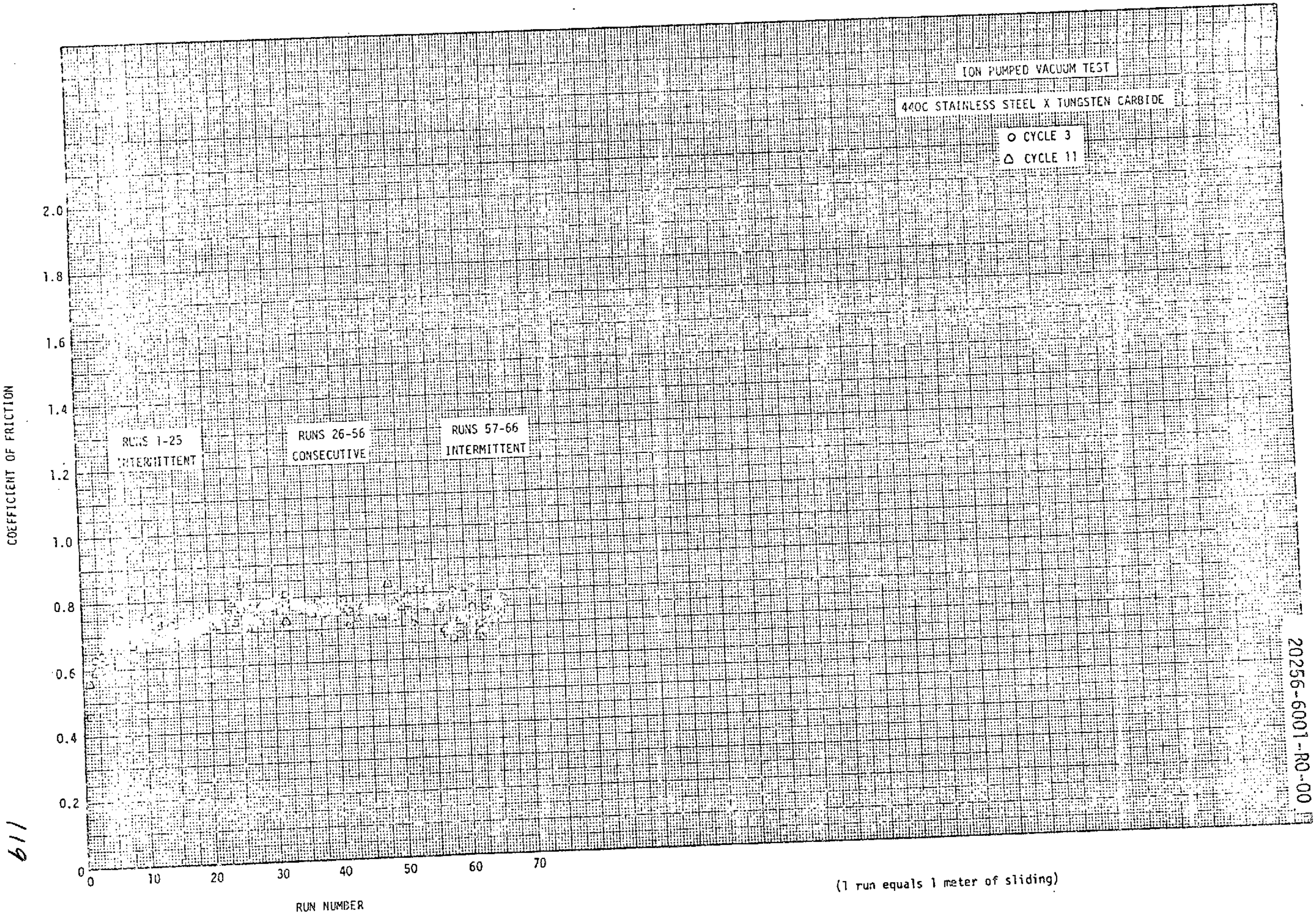
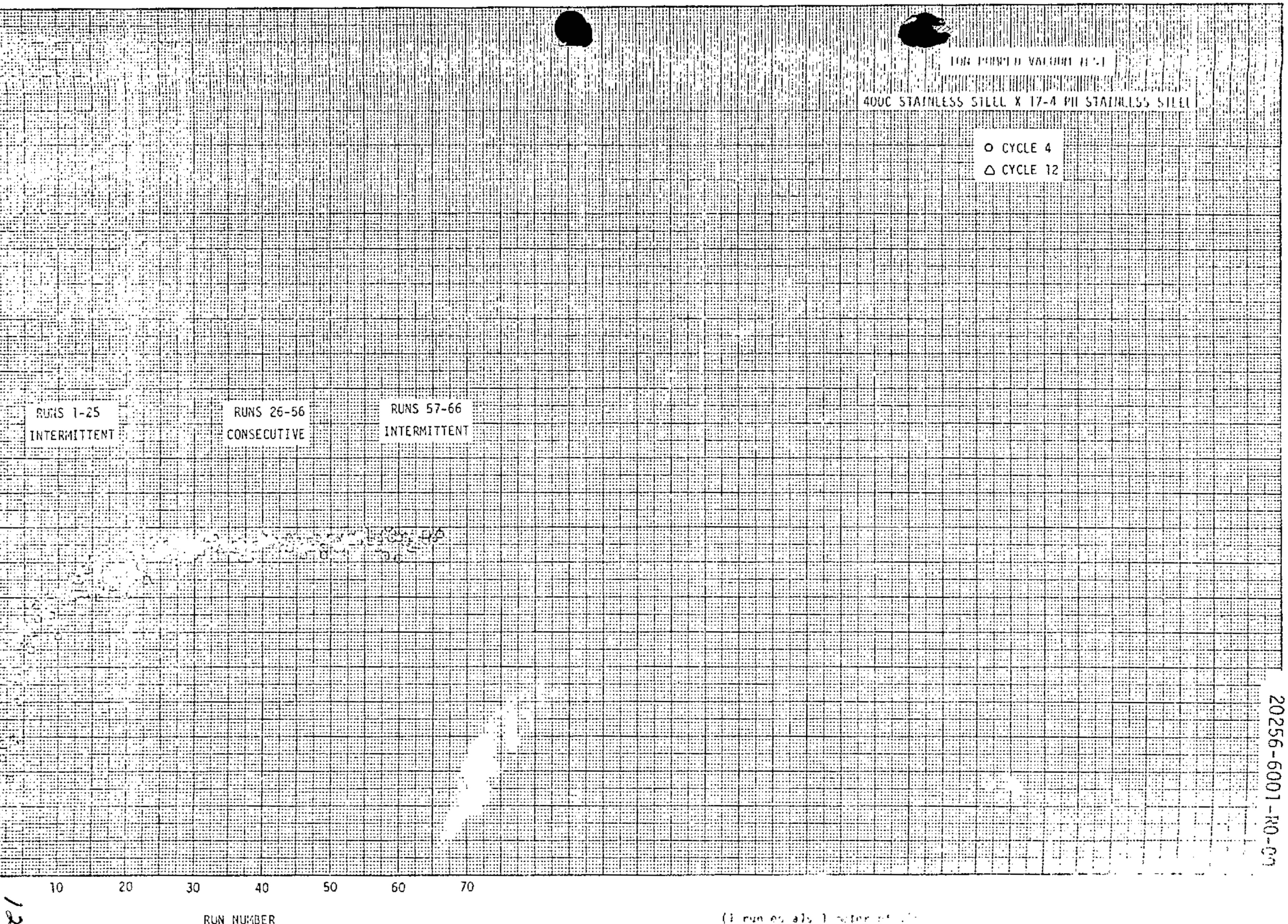

ION PUMPED VACUUM TEST
440C STAINLESS STEEL X SYNTHETIC MOLYBDENUM DISULFIDE
○ CYCLE 2
△ CYCLE 10
RUNS 1-25 INTERMITTENT
RUNS 26-56 CONSECUTIVE
RUNS 57-66 INTERMITTENT
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
RUN NUMBER

20256-6001

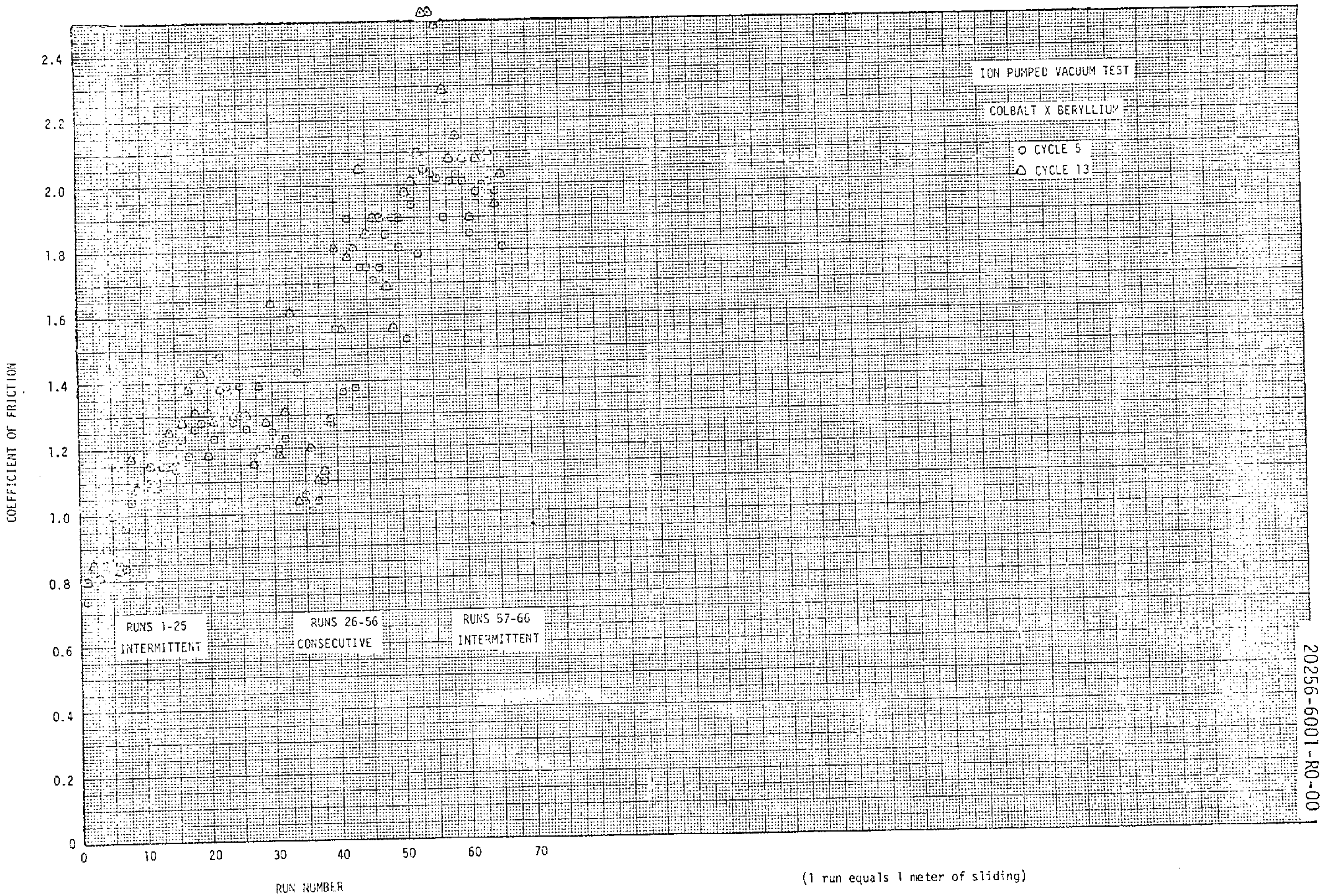


20256-6001-R0-00

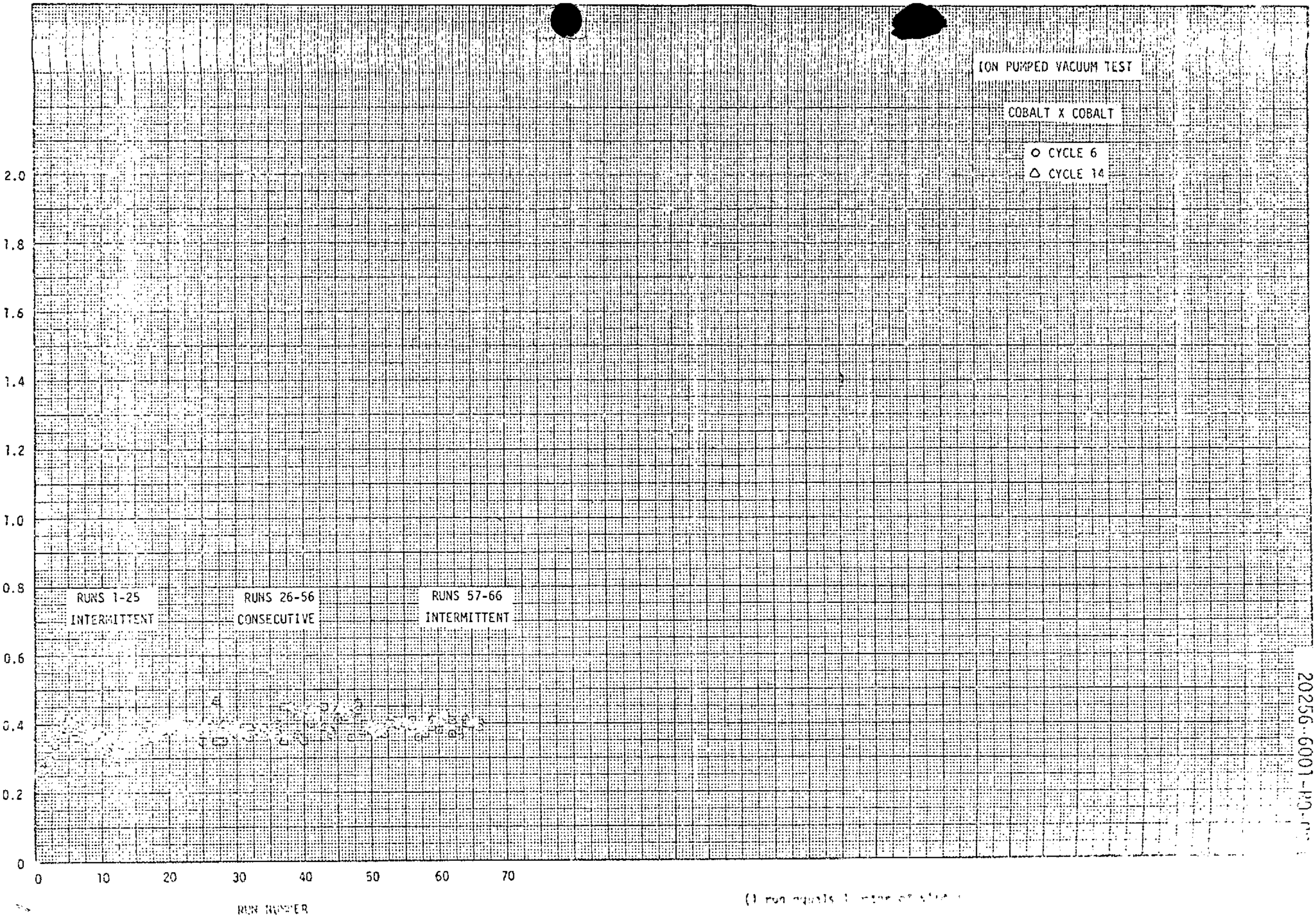


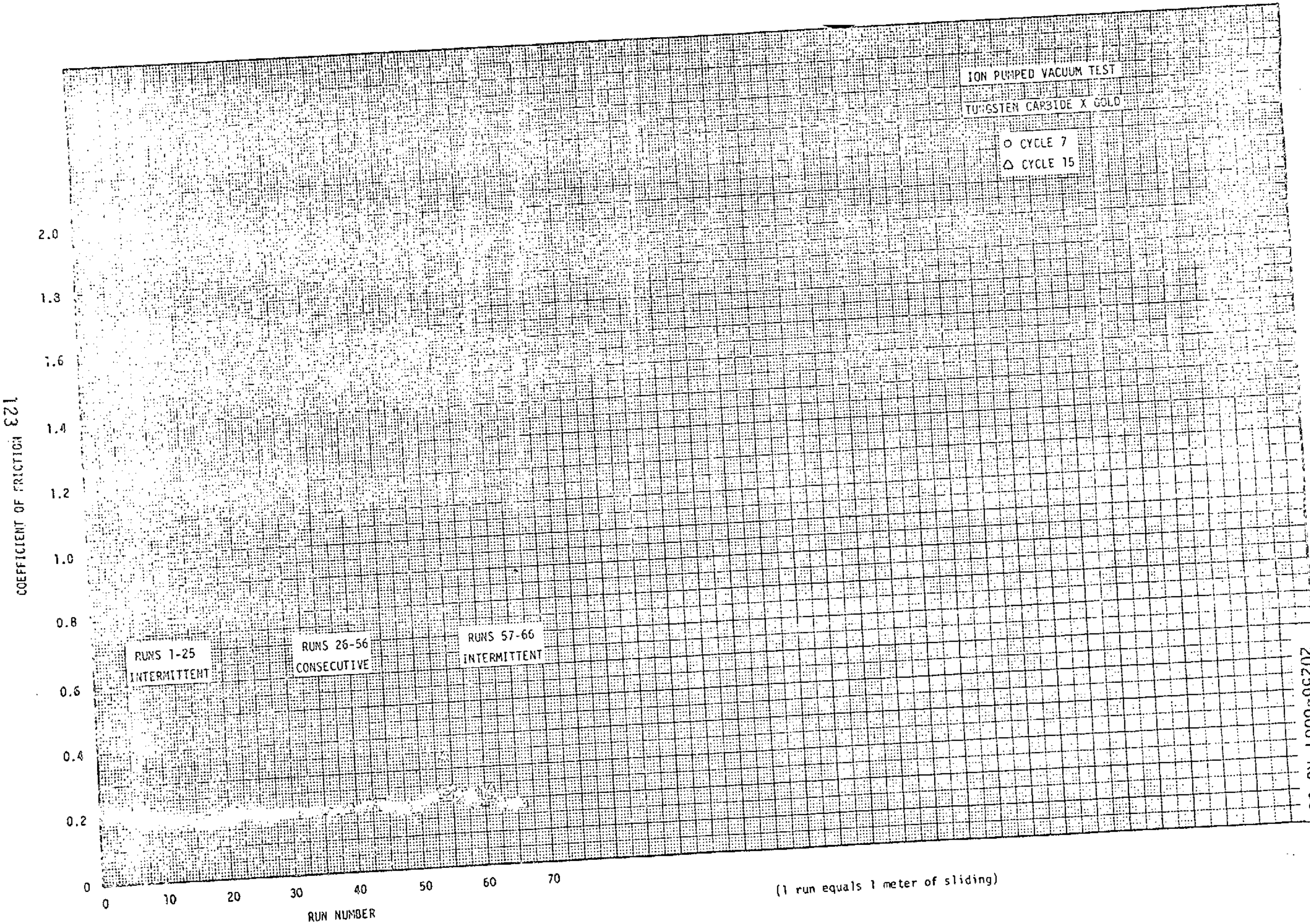
20256-6001-RO-00

120

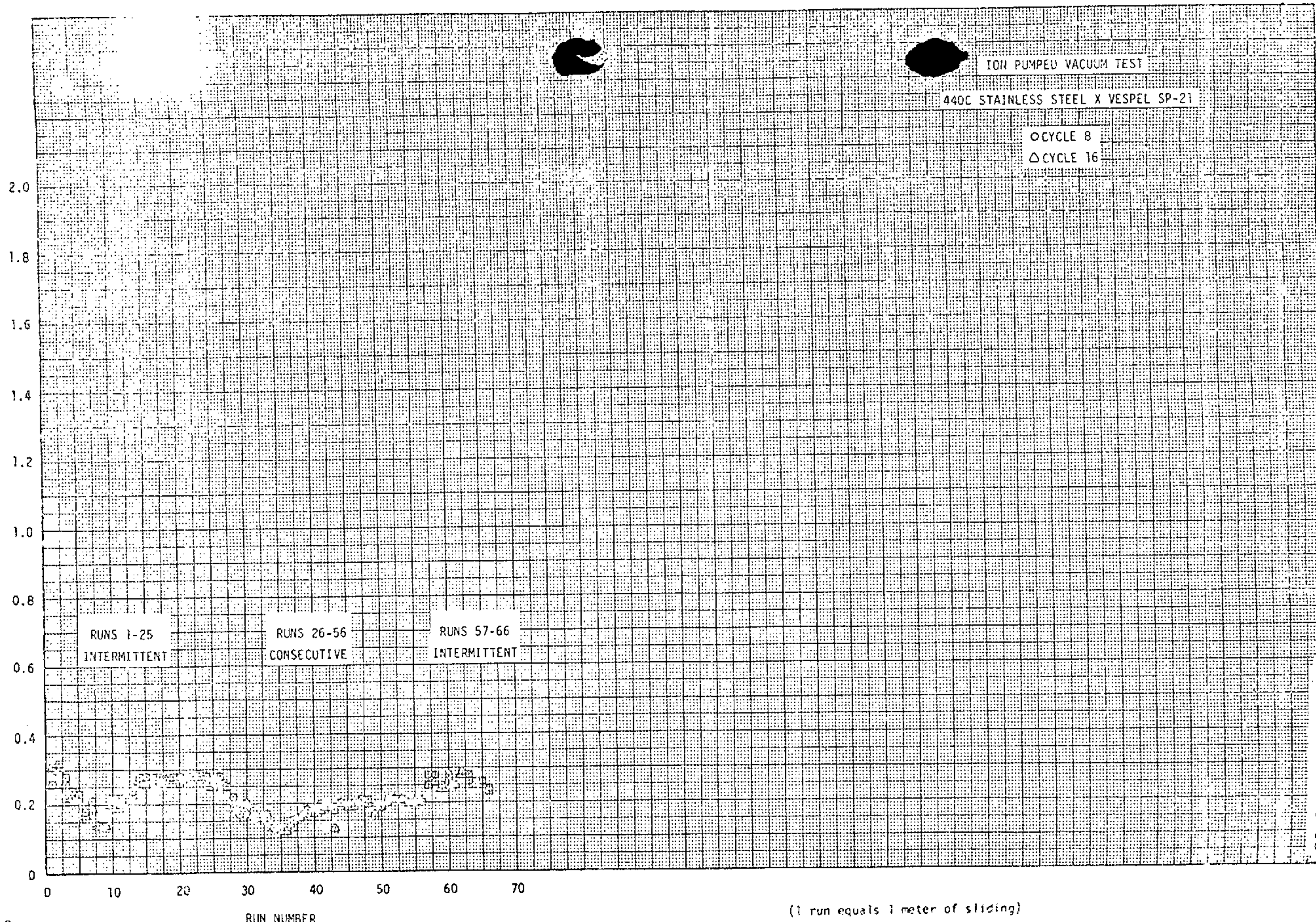


20256-6001-R0-00


ION PUMPED VACUUM TEST
COBALT X COBALT
O CYCLE 6
△ CYCLE 14
RUNS 1-25
INTERMITTENT
RUNS 26-56
CONSECUTIVE
RUNS 57-66
INTERMITTENT
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
RUN NUMBER

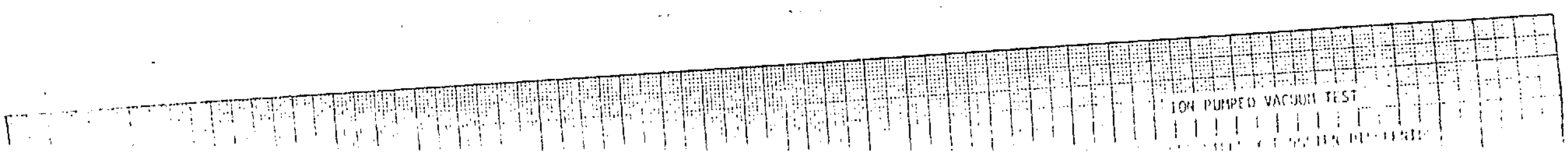


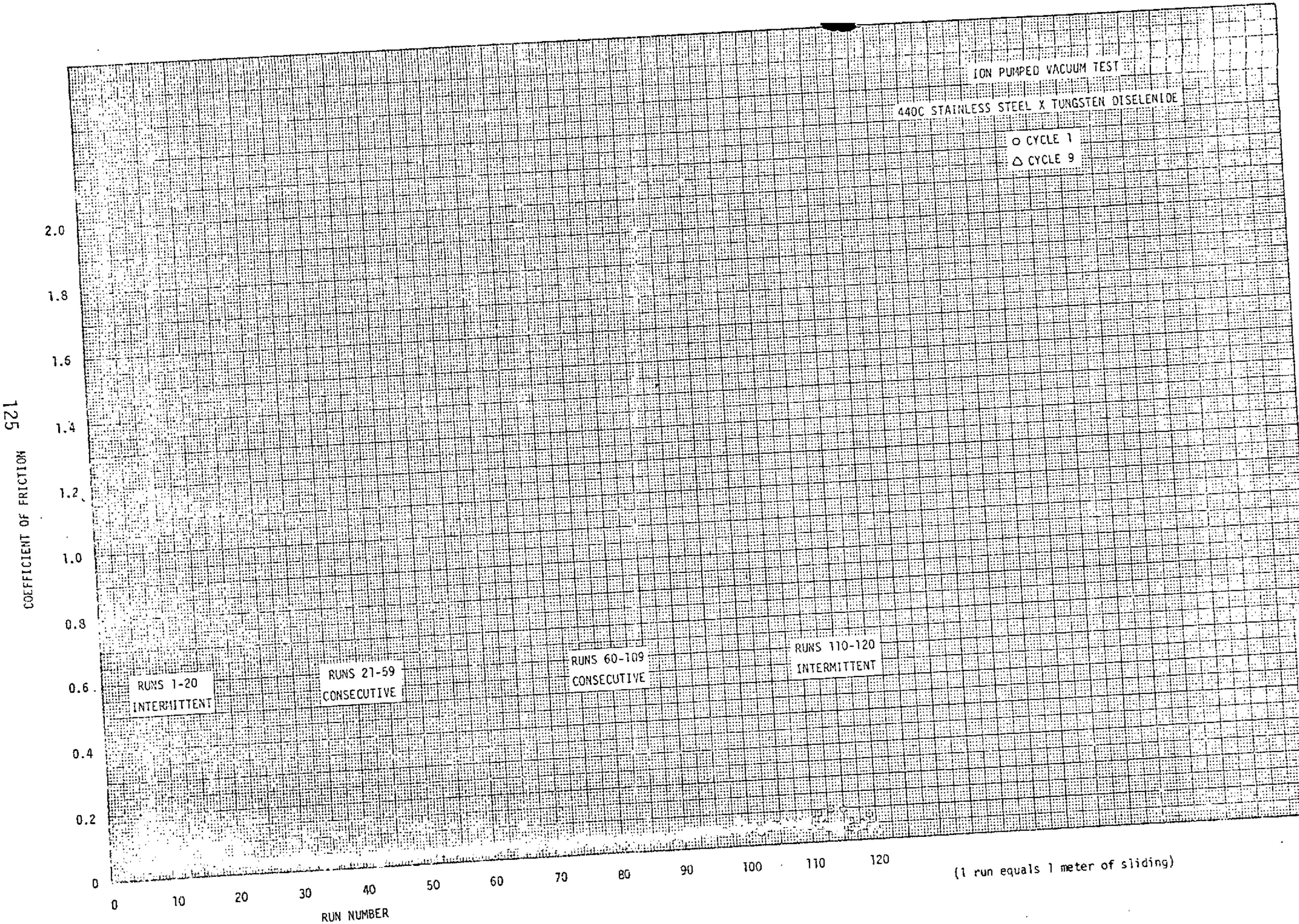
20256-6001-RU-00

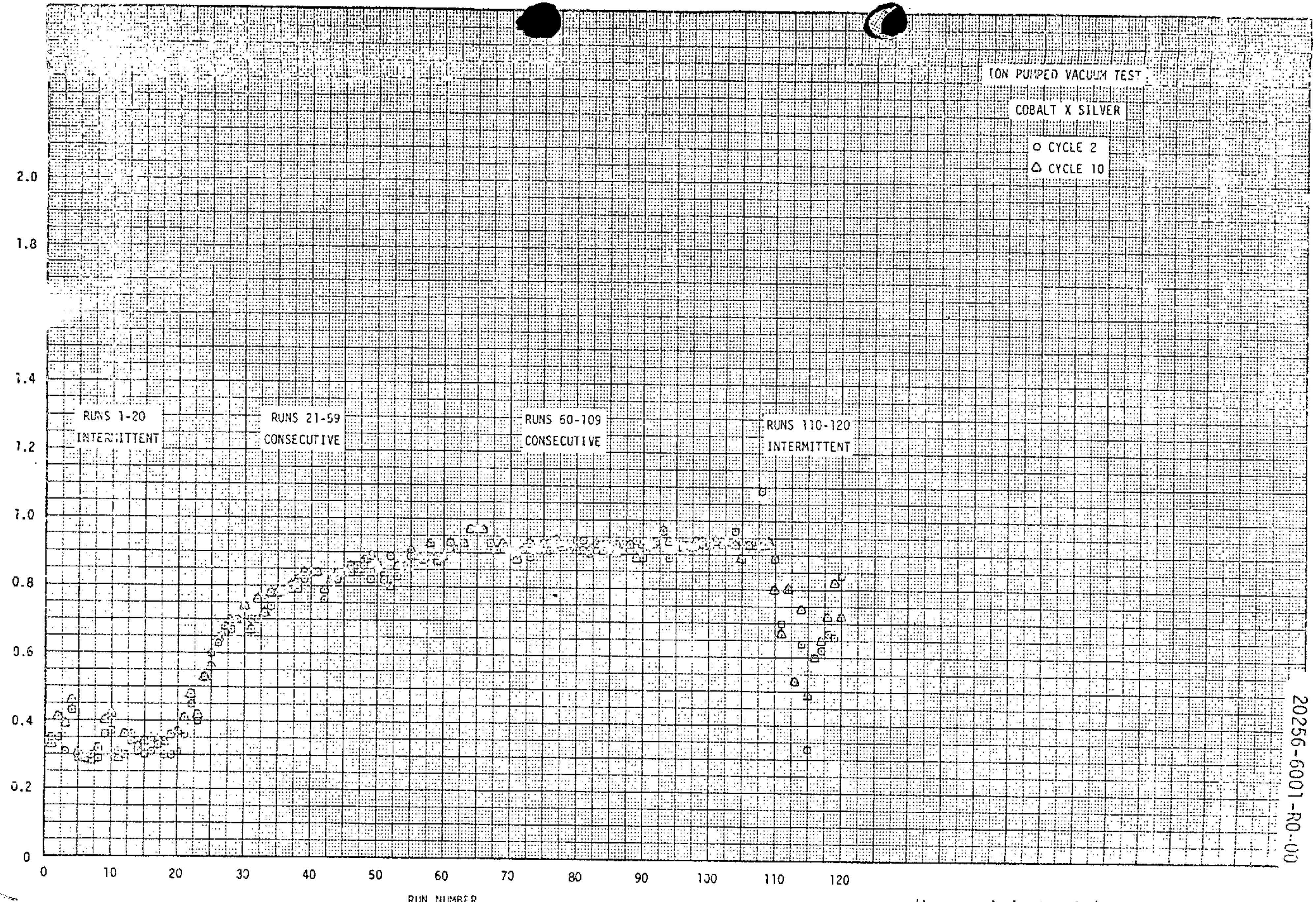


20256-6001-R0-00

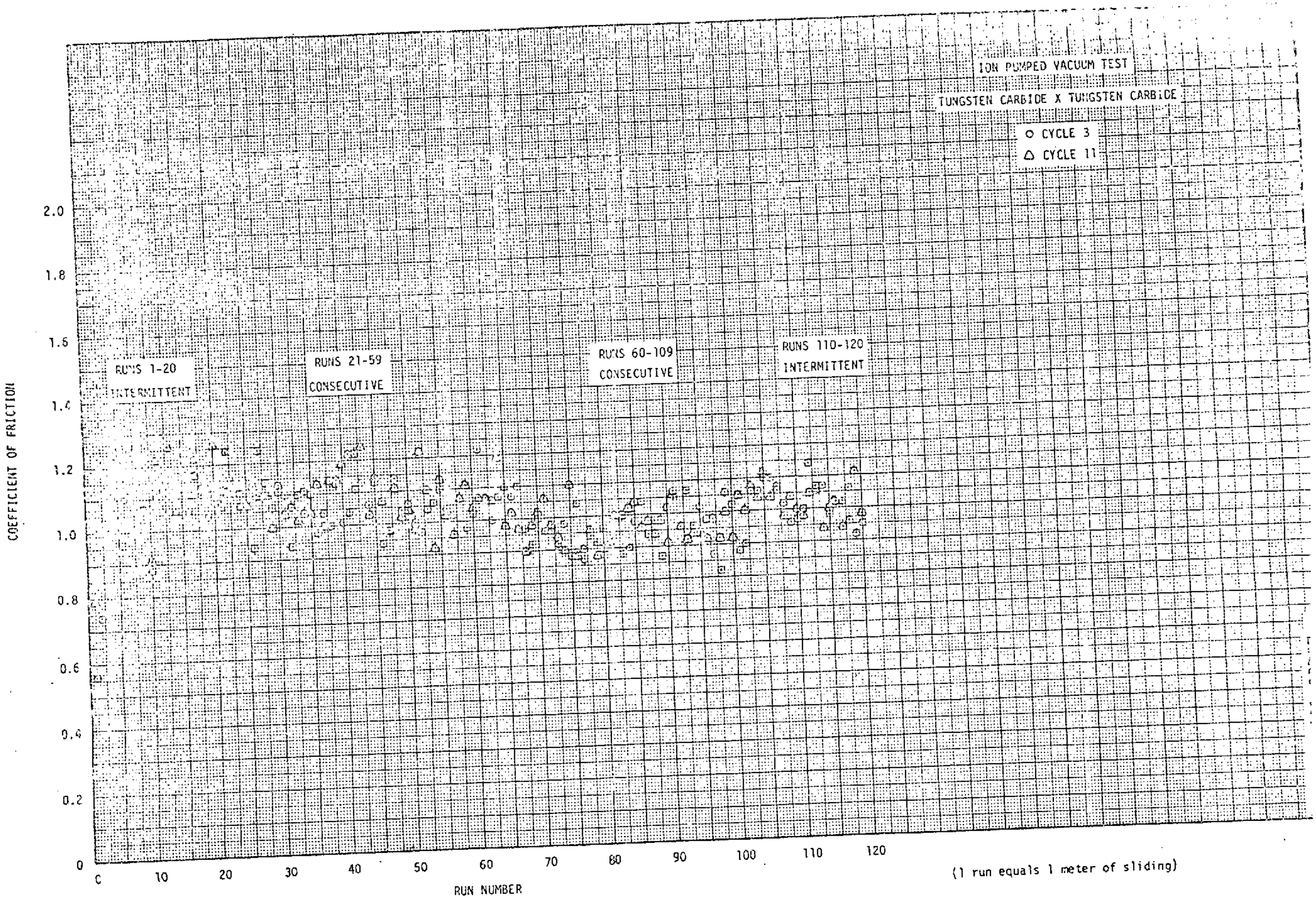
124



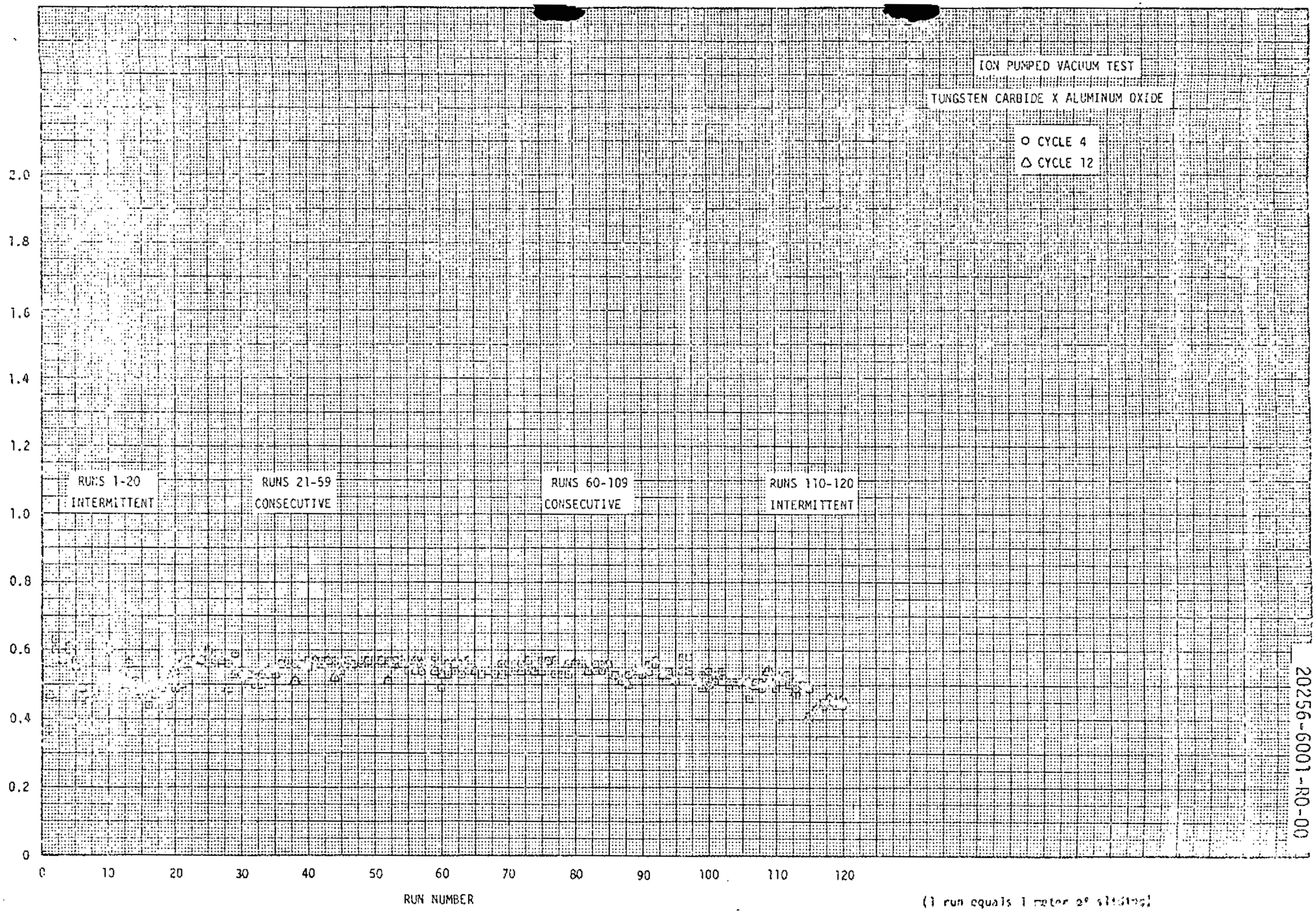

ION PUMPED VACUUM TEST
440C STAINLESS STEEL X TUNGSTEN DISELENIDE
○ CYCLE 1
△ CYCLE 9
COEFFICIENT OF FRICTION
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
RUNS 1-20
INTERMITTENT
RUNS 21-59
CONSECUTIVE
RUNS 60-109
CONSECUTIVE
RUNS 110-120
INTERMITTENT
0
10
20
30
40
50
60
70
80
90
100
110
120
RUN NUMBER
(1 run equals 1 meter of sliding)

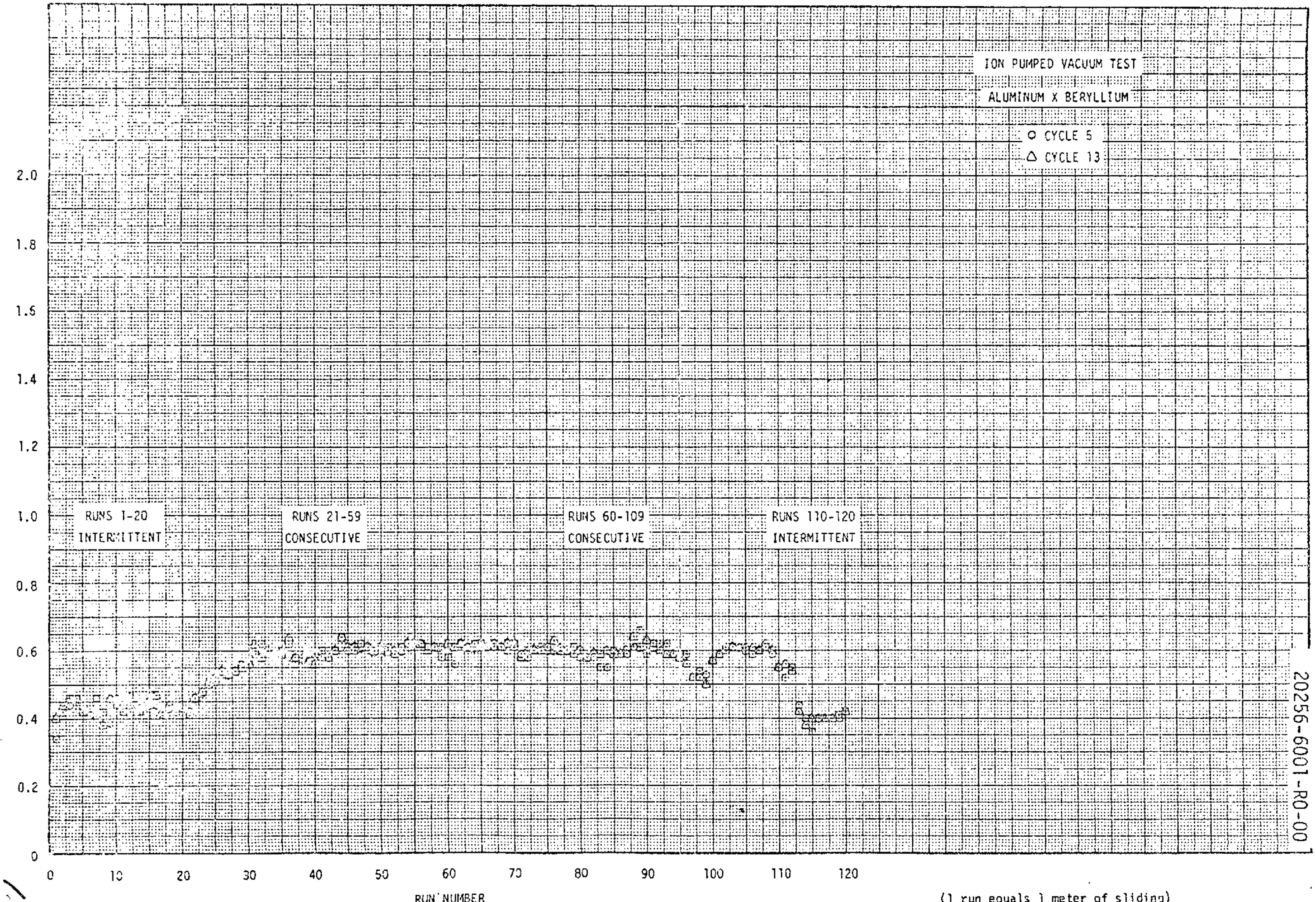

ION PUMPED VACUUM TEST
COBALT X SILVER
○ CYCLE 2
△ CYCLE 10
RUNS 1-20
INTERMITTENT
RUNS 21-59
CONSECUTIVE
RUNS 60-109
CONSECUTIVE
RUNS 110-120
INTERMITTENT
2.0
1.8
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
110
120
RUN NUMBER
20256-6001-R0-00

(1 run equals [illegible]



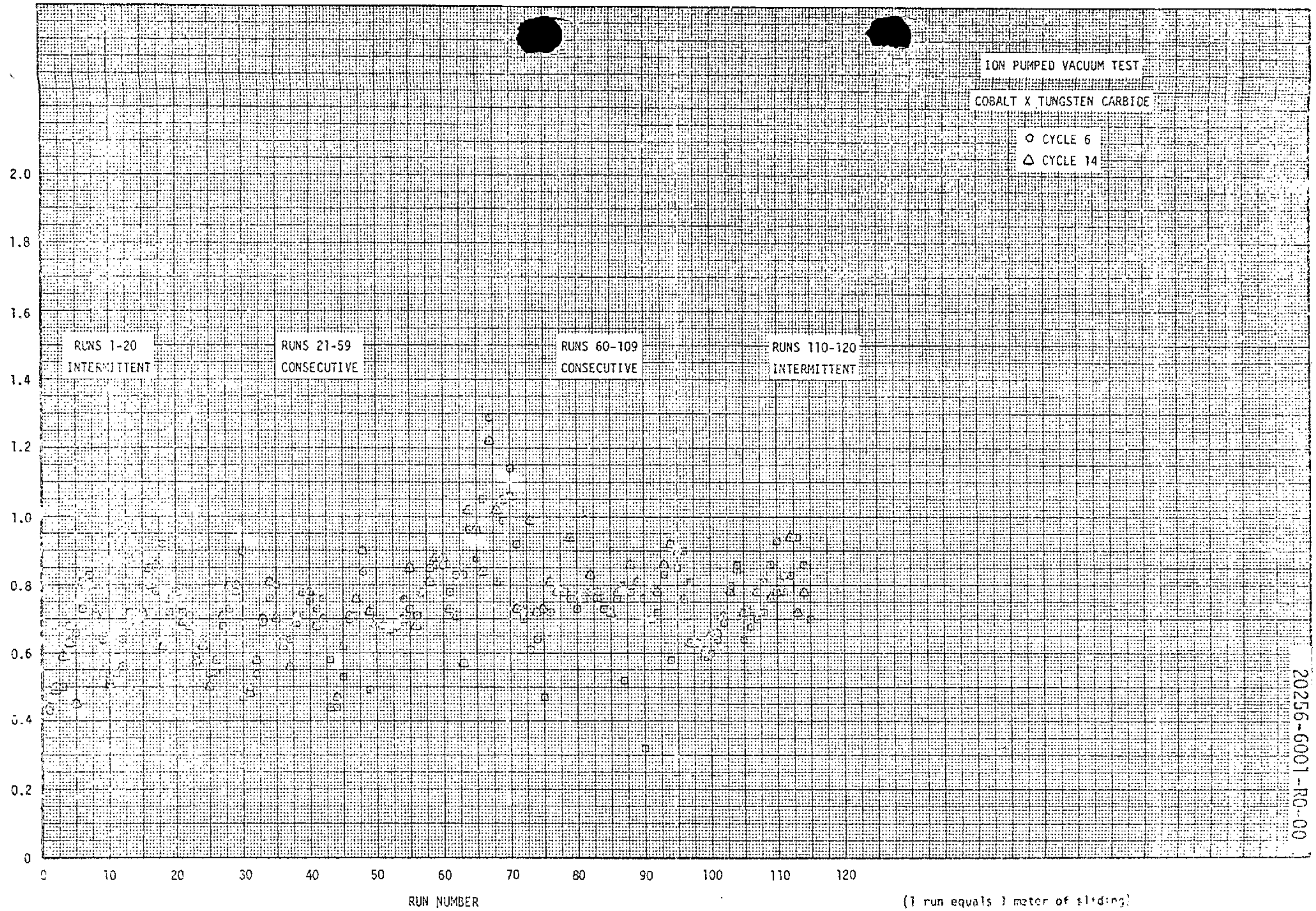
ION PUMPED VACUUM TEST
TUNGSTEN CARBIDE X TUNGSTEN CARBIDE
○ CYCLE 3
△ CYCLE 11
RUNS 1-20
INTERMITTENT
RUNS 21-59
CONSECUTIVE
RUNS 60-109
CONSECUTIVE
RUNS 110-120
INTERMITTENT
COEFFICIENT OF FRICTION
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
110
120
RUN NUMBER
(1 run equals 1 meter of sliding)


ION PUMPED VACUUM TEST
TUNGSTEN CARBIDE X ALUMINUM OXIDE
○ CYCLE 4
△ CYCLE 12
RUNS 1-20 INTERMITTENT
RUNS 21-59 CONSECUTIVE
RUNS 60-109 CONSECUTIVE
RUNS 110-120 INTERMITTENT
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0 10 20 30 40 50 60 70 80 90 100 110 120
RUN NUMBER
(1 run equals 1 meter of sliding)
20256-6001-R0-00



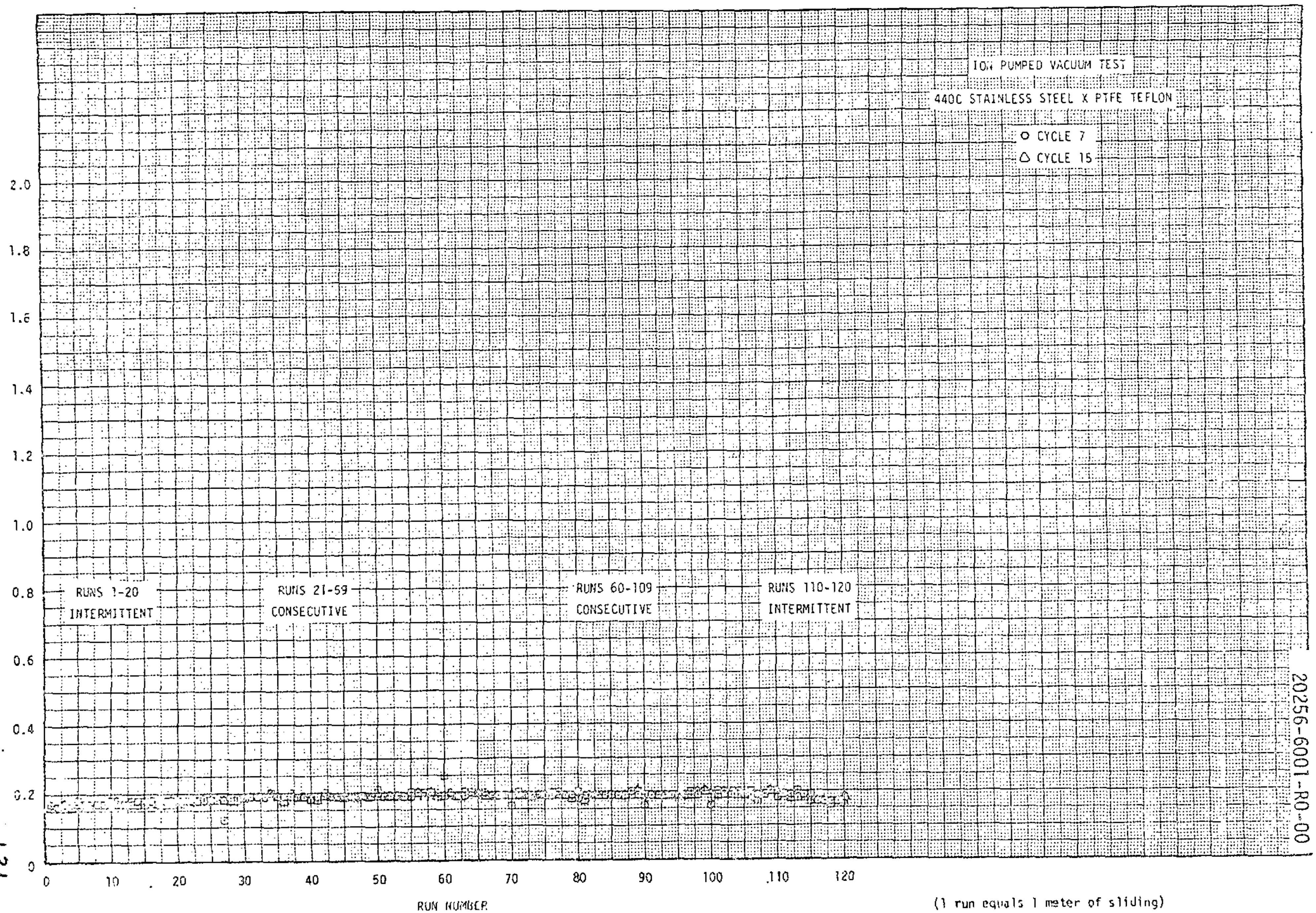
20256-6001-RO-00

125

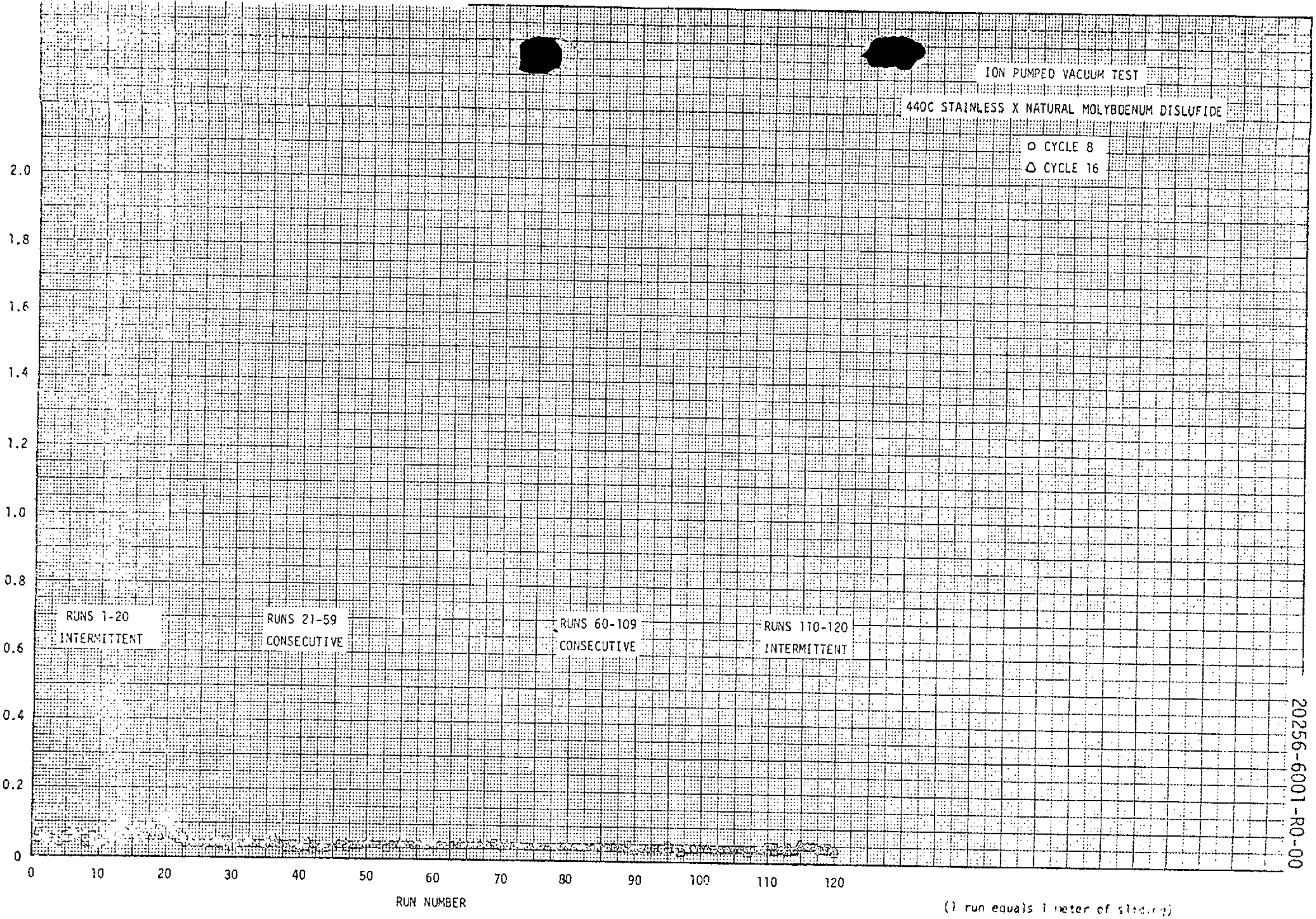


ION PUMPED VACUUM TEST
COBALT X TUNGSTEN CARBIDE
O CYCLE 6
△ CYCLE 14
RUNS 1-20 INTERMITTENT
RUNS 21-59 CONSECUTIVE
RUNS 60-109 CONSECUTIVE
RUNS 110-120 INTERMITTENT
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0 10 20 30 40 50 60 70 80 90 100 110 120
RUN NUMBER
(1 run equals 1 meter of sliding)
20256-6001-R0-00

130



ION PUMPED VACUUM TEST
440C STAINLESS STEEL X PTFE TEFLON
○ CYCLE 7
△ CYCLE 15
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
RUNS 1-20 INTERMITTENT
RUNS 21-59 CONSECUTIVE
RUNS 60-109 CONSECUTIVE
RUNS 110-120 INTERMITTENT
0
10
20
30
40
50
60
70
80
90
100
110
120
RUN NUMBER
(1 run equals 1 meter of sliding)
20256-6001-R0-00



ION PUMPED VACUUM TEST
440C STAINLESS X NATURAL MOLYBDENUM DISLUFIDE
○ CYCLE 8
△ CYCLE 16
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
RUNS 1-20
INTERMITTENT
RUNS 21-59
CONSECUTIVE
RUNS 60-109
CONSECUTIVE
RUNS 110-120
INTERMITTENT
0
10
20
30
40
50
60
70
80
90
100
110
120
RUN NUMBER
(1 run equals 1 meter of sliding)
20256-6001-RO-00

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REFERENCES

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2. R. L. Hammel, "In-Space Friction Tests", AFRPL-TR-69-207, Air Force Rocket Propulsion Laboratory, Edwards, California, November 1969.

3. R. L. Hammel, H. J. Horn and H. T. Sliff, "Environmental Research Satellites for In-Space Friction Experiments - System Description Document", TRW Systems, Redondo Beach, California, Document No. 05319-6016-RO-00, July 1967.

4. "Environmental Research Satellite No. 20 - Operations Plan", NASA/GSFC, Greenbelt, Maryland, Document No. X-513-67-128, March 1967.

5. R. L. Hammel, "AFRPL Ground Test Friction Experiment Operations Manual, TRW Systems, Redondo Beach, California, Document No. 12644-6001-TO-00, June 1969.

6. R. L. Hammel, "Molecular Sink Vacuum Friction Test", AFRPL-TR-69-208, Air Force Rocket Propulsion Laboratory, Edwards, California, November 1969.