MRL-R-896 (11) AR-003-309

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

MATERIALS RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AD A139721

REPORT

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THE MRL SMALL SCALE GAP TEST FOR THE ASSESSMENT OF SHOCK SENSITIVITY OF HIGH EXPLOSIVES

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The MRL SSGT has proved to be a simple, convenient and relatively cheap method for the assessment of shock sensitivity. Results are reproducible and provide a good indication of relative shock sensitivity.

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SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-R-896	AR-003-309	UNCLASSIFIED

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REPORT DATE	TASK NO.	SPONSOR
AUGUST, 1983	DST 82/169	DSTO

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Superintendent, MRL
Physical Chemistry Division

SECONDARY DISTRIBUTION

Approved for Public Release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

SENSITIVITY
EXPLOSIVE SENSITIVITY
SHOCK SENSITIVITY
GAP TEST
FIRING CELL

COSATI GROUPS 1901

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The report describes a small scale gap test (SSGT) used at MRL for the assessment of shock sensitivity of high explosives. Details of the test assembly, procedure and analysis of results, along with results for a range of explosives and explosive compositions are presented. A specially designed explosive firing cell is also described.

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CONTENTS

THE MRL SMALL SCALE GAP TEST FOR THE ASSESSMENT OF SHOCK SENSITIVITY OF HIGH EXPLOSIVES

1. INTRODUCTION

Secondary explosives are normally initiated by the application, either directly or through an inert barrier, of an explosively generated shockwave. This shockwave is produced by a donor charge composed of either primary or secondary explosive. The ease with which an explosive detonates in response to the passage of a shockwave is termed its shock sensitivity. If the shock sensitivity of an explosive can be characterised then reliable initiating systems can be designed for it.

Various forms of gap test have been used to assess shock sensitivity over the past fifty years, probably the first being reported in France by Muraour [1] in 1933. This method was later developed in the UK by Pape and Whitbread [2] and in the USA by Edwards and Rice [3]. In 1958 Cachia and Whitbread [4] presented results of instrumented gap tests. However the best known gap tests are probably those developed by Naval Surface Weapons Center (formerly Naval Ordnance Laboratories) in the USA [5-9], where both small and large scale calibrated gap tests are used to determine the shock sensitivity of high explosives and propellants.

Since 1965 MRL have used a small scale gap test (SSGT) similar to that described by Cachia and Whitbread [4]. Basically the test assembly consists of four components (Fig. 1).

1. An explosive donor charge.
2. A brass shock attenuator (gap).
3. An acceptor charge (the explosive under test).
4. A mild steel witness block for detecting detonation.

By varying the gap thickness until the acceptor detonates in 50% of firings, the critical gap thickness ($m_{50\%}$) can be determined. The test is relatively cheap and simple to perform and generally requires only 25-30 shots to be fired. The results provide an indication of relative shock sensitivity and are very reproducible.

2. TEST ARRANGEMENT

The MRL SSGT arrangement is shown in Fig. 1.

2.1 The Donor

The basic (Scale 1) donor consists of an MRL manufactured exploding bridgewire (EBW) detonator filled with PETN, initiated by a 3.0 kV, 1μF capacitor discharge firing circuit. The EBW detonator was chosen because it was readily accessible and proved to be a very reproducible donor containing a conveniently small amount of explosive. However for relatively insensitive explosives, which cannot be initiated by a bare Scale 1 donor, a more powerful (Scale 2) donor is required. The Scale 2 donor consists of a Scale 1 donor whose output is boosted by the addition of a small pressed PETN charge, 10.2 mm dia. x 3.8 mm and density 1.63 Mg/m^3.

2.2 The Gap

The shock attenuating gap consists of a 20 mm square of laminated brass shim. This material is commercially available in sheets of 900 mm x 150 mm and consists of 0.051 mm (0.002 inch) thick layers of brass shim bonded together by a very thin film of solder; sheet thicknesses from 0.4 mm to 2.4 mm are available. Single or multiple laminations can be readily peeled off with the aid of a knife, allowing gaps of various thickness to be prepared.

2.3 The Receptor

Explosive test pieces or receptors are usually pressed or cast and machined, although granular, liquid, plastic (see 2.6) and sheet explosive can also be tested. It has been shown [4] that good discrimination between fading and developing shocks is achieved in a receptor of length 25.4 mm, and well defined critical gap thicknesses are obtained. (The use of a longer receptor would give even better results). The receptors are therefore normally cylinders 12.7 mm dia. x 25.4 mm long or cuboids 12.7 mm x 12.7 mm x 25.4 mm long depending on the method of fabrication. When testing sheet explosive a 25 mm stack of 12.7 mm squares of the sheet is used as the receptor.

2.4 The Witness Block

The witness block is 25.4 mm x 25.4 mm x 12.7 mm thick mild steel. When testing low power explosives an aluminium witness block can be used. This will increase the depth of dent by a factor of about 3 compared with mild steel, making it easier to discriminate between detonations and non-detonations.

2.5 *The Test Assembly*

The components are assembled with the aid of a jig, starting with the witness block and finishing with the donor on top. The assembly is held together by a rubber band and components are adjusted for axial alignment. It is then ready to be placed inside the explosive firing cell.

2.6 *A Modified Test Assembly for Liquid, Plastic or Granular Explosives*

Where the acceptor explosive is not mechanically self supporting, it is contained in a thin walled brass tube with a thin brass shim soldered over one end. The tubing normally used has an outside diameter of 17.7 mm and a wall thickness of 0.5 mm. The length is normally 25.4 mm but can be increased if necessary to suit the build-up characteristics of the explosive being tested.

When using the brass tube the assembly is inverted (Fig. 2) so that the detonator is at the the bottom, with the gap and then the tube mounted on top of it. The thickness of the brass shim soldered to the base of the tube added to that of the laminated brass shim is taken as the gap thickness. The witness block is then placed on top of the explosive.

3. FIRING FACILITY

3.1 *The Building*

As the gap test assembly time is short, a high testing rate (about 12 shots/h) is possible. With this in mind a special compact firing facility was designed (Fig. 3). The layout minimises walking between the charge preparation, firing cell and control rooms without compromising safety. The 18 m^2 building has a light roof and 230 mm thick reinforced concrete walls. A sliding steel door is used to separate the firing cell room from the rest of the building.

3.2 *The Explosive Firing Cell*

An explosive firing cell (Figs. 4 and 5) with a 20 g explosive limit was specially designed [10] and installed in the firing cell room. The cell is basically a 12.7 mm thick steel cylinder having an overall length of 1220 mm and outside diameter of 965 mm. One end is flanged with a 610 mm opening which is closed by a 38 mm thick circular steel door and locked in position by twelve cam operated latches. The other end is closed by a welded 16 mm thick torispherical steel plate. Venting is through the bottom of the cell via a right angled steel pipe to the outside of the building. Fumes are exhausted by a *Jetflow* air mover into a water trap.

The firing pad is mounted on the inside of the door so that when the door is closed the test assembly is at the centre of the firing cell. To facilitate setting up, the door is withdrawn on linear bearings so that the firing pad is outside the cell. Insulated terminal posts are mounted through the door for connection to the detonator on the inside and the high voltage firing unit on the outside. An additional four terminal posts are provided for possible instrumentation.

3.3 Safety Interlocks

A *Castell* lock ensures that firing cannot proceed unless the firing cell door is locked. This allows the *Castell* key to be removed and used in the firing control room to arm the firing circuit. A microswitch interlock on the sliding steel door (Fig. 3) ensures against firing with that door open.

4. TEST PROCEDURE

4.1 Preparation of the Test Assembly

Explosive acceptor charges are visually inspected for imperfections and in some cases are radiographed. Acceptors with cracks or cavities, which could affect the shock initiation properties of the explosive, are normally excluded from the test. The end faces of the acceptor should be flat and perpendicular to the axis. Important details of explosive type, composition, preparation, fabrication and density are recorded.

The brass laminate shims comprising the gap should be flat and the edges free from burrs so that, when a gap consisting of more than one shim is used, good surface to surface contact between shims is assured. Where an assemblage of shims is used to produce the desired gap, the thickest shim should be in contact with the donor. It is important that there are no air gaps between shims or at the donor/gap and acceptor/gap interfaces.

Historically gaps have been measured in thousandths of an inch (mils) and as current stocks of shim material are in imperial sizes (2 mil laminations) it is convenient to measure and record the gap thickness in these units. Gap thickness is measured using a micrometer and must be within 0.0002 inch (0.005 mm) of the selected value to be acceptable.

Using a simple jig (Fig. 6) the acceptor is placed on the witness block, the gap centrally on top of the acceptor and the donor centrally on top of the gap, and the whole assembly is held together with a rubber band. The assembly is placed on the firing pad in the explosive firing cell and the firing lead carefully fitted to the EBW donor. Before closing the firing cell door a final check is made to ensure components of the assembly are in line.

4.2 Conduct of Test

Assuming the critical gap of the explosive to be tested is unknown, a series of ranging shots is fired to determine an approximate value. That is, a gap thickness is chosen based on experience with similar explosives. If the acceptor detonates, as indicated by a sharply defined dent in the witness block (Fig. 7), then the gap is doubled for the next test. If failure to detonate results then the gap is halved. This procedure is followed until a detonation and a failure are obtained, and then a gap thickness is chosen half way between the largest gap which allowed detonation and the smallest which prevented it. Using this method the critical gap can usually be estimated with about five ranging shots.

To determine an accurate value of shock sensitivity a larger number of shots must be fired using gap thicknesses near the estimated critical gap and the results analysed statistically (Appendix 1). For this purpose the Bruceton Up-Down method reported by Dixon and Mood [11] is used.

1. A gap thickness h near the estimated critical gap is chosen for the first shot and an interval d is selected as the difference in thickness between the gaps to be used (barrier thickness interval).

2. If the first shot results in detonation the second shot is fired with a gap thickness of h + d, if it fails to detonate the second shot is fired with a gap thickness of h - d.

3. This Up-Down procedure is continued for 25-30 shots, increasing or decreasing the gap thickness by d each time depending on whether the acceptor detonates or fails.

Where the estimated critical gap exceeds 1 mm (0.040 inch) a value of d = 0.10 mm (0.004 inch) is used. Where the estimated critical gap does not exceed 1 mm (0.040 inch) a value of d = 0.05 mm (0.002 inch) is used.

Appendix 1 includes a sample "Gap Test Assessment of Shock Sensitivity" *proforma* showing how the results are recorded.

5. ANALYSIS OF RESULTS

The Dixon and Mood [11] method of analysis set out in Appendix 1 is used to determine the 50% firing gap thickness ($m_{50\%}$), usually referred to as the critical gap.

Briefly the critical gap is given by

$$m_{50\%} = c + d\left(\frac{\Sigma i n_i}{\Sigma n_i} \pm \frac{1}{2}\right)$$

Where c = smallest gap thickness at which detonation is recorded.
d = gap thickness interval between shots (i.e. 2 mils or 4 mils).
i = a number given to each gap thickness starting with c as zero.
n_i = number of detonations/non-detonations (failures); use whichever has the smaller total number. Use a +ve sign in the equation when using detonations or a -ve sign when using non-detonations.

The standard deviation (σ) and the 95% confidence limits ($L_{95\%}$) are determined using these results in conjunction with the table and graphs published by Dixon and Mood [11], and reproduced in Appendix 1.

6. RESULTS

Tables 1A and 1B list MRL SSGT data for a few well known explosives and explosive compositions; many of these results will have been reported previously by research workers at these laboratories.

Care should be taken to differentiate between results obtained using the Scale 1 and 2 donors as direct correlation between scales is not possible; for this reason explosive compositions which would detonate using Scale 1 are sometimes tested on Scale 2 to enable comparison with other compositions which will not detonate on Scale 1.

It can be seen that in order of increasing shock sensitivity we have TNT, Tetryl, RDX and PETN; furthermore the shock sensitivity of each explosive decreases as its packing density is increased. For a given composition a pressed charge is more shock sensitive than a cast charge.

Coating or mixing with an inert wax or plastic decreases shock sensitivity. For example RDX in PE4 and SX2, or RDX coated with polyethylene wax [12,13] all show a marked decrease in shock sensitivity. Similarly when PETN is mixed with silicone rubber its shock sensitivity is decreased. It should be noted that EDC8, Batch CY 52, purchased from the UK, was known to have an abnormally high shock sensitivity.

There are many variables which control shock sensitivity that are not evident in the results presented here. Shock sensitivity work carried out by many workers is conveniently summarized by J. Roth in the *Encyclopedia of High Explosives* [14]. Not only are the above observations confirmed but many factors controlling shock sensitivity, including packing density, particle size, shock duration, shock geometry, temperature, inert coatings and interstitial gas, are examined.

Shock sensitivity is a measure of explosive performance rather than a hazard assessment, although detonation is a potential hazard. Therefore the use of SSGT data alone is not recommended for hazard assessment. However it is worth noting that R. Peterson [15] has ranked sixty-two explosives in a "Susceptibility Index" (SI). He examined results from a range of sensitivity tests, including large and small scale gap tests, and developed equations to convert test results to SI values.

7. CONCLUSIONS

The MRL SSGT is a simple, convenient and relatively cheap method for the assessment of shock sensitivity of high explosives and has proved most useful. However it must be remembered that the results, although very reproducible, only provide indications of *relative shock sensitivity*.

There are no plans to calibrate the donor/gap system in more absolute terms of shock strength. Future work will be confined to developing a computer programme to perform the statistical analysis of results.

8. ACKNOWLEDGEMENTS

Over the years many people have been involved with gap testing at MRL. In particular the efforts of the late Reg Rix, Algis Pleckauskas and most recently, Franjo Somodji are gratefully acknowledged.

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TABLE 1A - SHOCK SENSITIVITY RESULTS OBTAINED USING THE MRL SSGT

EXPLOSIVE	DETAILS	DENSITY (Mg/m^3)	DONOR SCALE	$m_{50\%}$ (mils)	$L_{95\%}$ (mils)
RDX	Granular	≈ 1.06	1	214	210-219
RDX	RD 1347, Pressed	1.66	1	146	140-152
PE4	88% RDX, Plastic Explosive	1.59	1	21.7	20.8-22.6
SX2	88% RDX, Sheet Explosive, ex UK	N/A	1	20.8	19.3-22.3
PETN	Powder, FSSS = 770 cm^2/g	≈ 0.86	1	268	257-280
PETN	Powder, FSSS = 2190 cm^2/g	≈ 0.90	1	272	264-280
CE (Tetryl)	Pressed	≈ 1.48	1	112	106-117
TNT	Pressed	≈ 1.52	1	48.0	47.1-48.9
TNT	Pressed	1.49	1	27.1	26.5-27.6
RDX/Polyethylene Wax	92/8, Pressed, AC 629 Wax	1.615	1	68.7	64.4-72.9
RDX/Polyethylene Wax	" " "	1.579	1	62.7	60.8-64.6
RDX/Polyethylene Wax	" " "	1.539	1	37.7	35.8-39.5
RDX/TNT	70/30, Pressed	1.44	1	100	99-102
RDX/TNT	60/40, Pressed	1.41	1	96.3	93.9-98.7

N/A = Not Available

TABLE 1B - SHOCK SENSITIVITY RESULTS OBTAINED USING THE MRL SSGT

EXPLOSIVE	DETAILS	DENSITY (Mg/m^3)	DONOR SCALE	$m_{50\%}$ (mils)	$L_{95\%}$ (mils)
RDX/TNT	55/45, Cast, ex EFM	1.65	1	14.3	11.3-17.3
RDX/TNT/Beeswax	55/45/1, Cast	N/A	1	15.4	14.3-16.6
PETN/TNT	50/50 "Pentolite", Cast, ex ICI	≈ 1.65	1	31.6	30.0-33.2
PETN/TNT	60/40, Cast	≈ 1.7	1	64.0	60.2-67.8
HMX/TNT	60/40, Cast	≈ 1.7	1	13.8	11.9-15.7
EDC/8	76/24 PETN/Si Rubber, CY 52, ex UK	N/A	1	99.2	96.9-101.5
ICI "Metabel"	70% PETN, Sheet Explosive	≈ 1.6	1	80.7	75.0-86.4
RDX/TNT/Al/Wax	ex Soviet 122 mm Rocket Warhead	N/A	1	5.0	4.1- 5.9
RDX/TNT/Beeswax	55/45/1, Recrystallised Gd. 1A RDX	1.704	2	16.7	15.7-17.7
RDX/TNT/Beeswax	55/45/1, Milled & Boiled Gd. 1B RDX	1.696	2	34.2	32.9-35.4
RDX/TNT/Beeswax	60/40/1, Gd. 1A RDX	1.708	2	19.7	18.0-21.3
RDX/TNT/Beeswax	60/40/1, Gd. 1B RDX	1.704	2	40.6	39.1-42.2

N/A = Not available

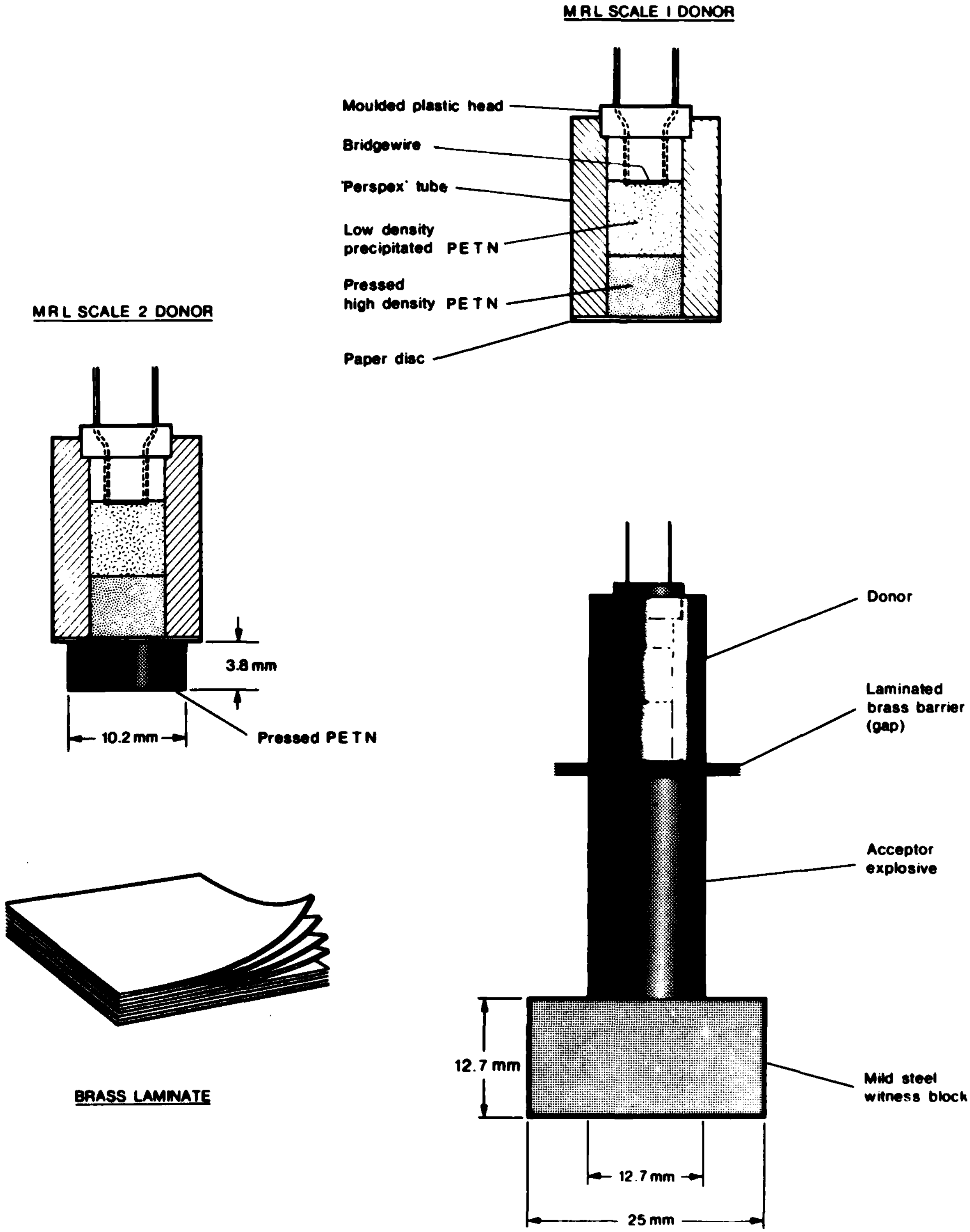


FIGURE 1. The MRL small scale gap test (SSGT) assembly.

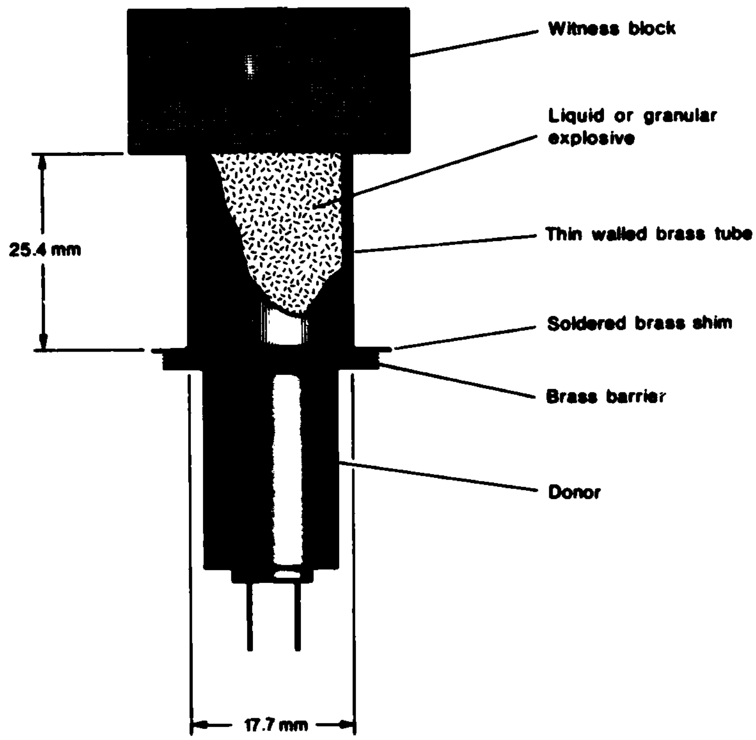


FIGURE 2. Modified gap test assembly for liquid, plastic or granular explosives.

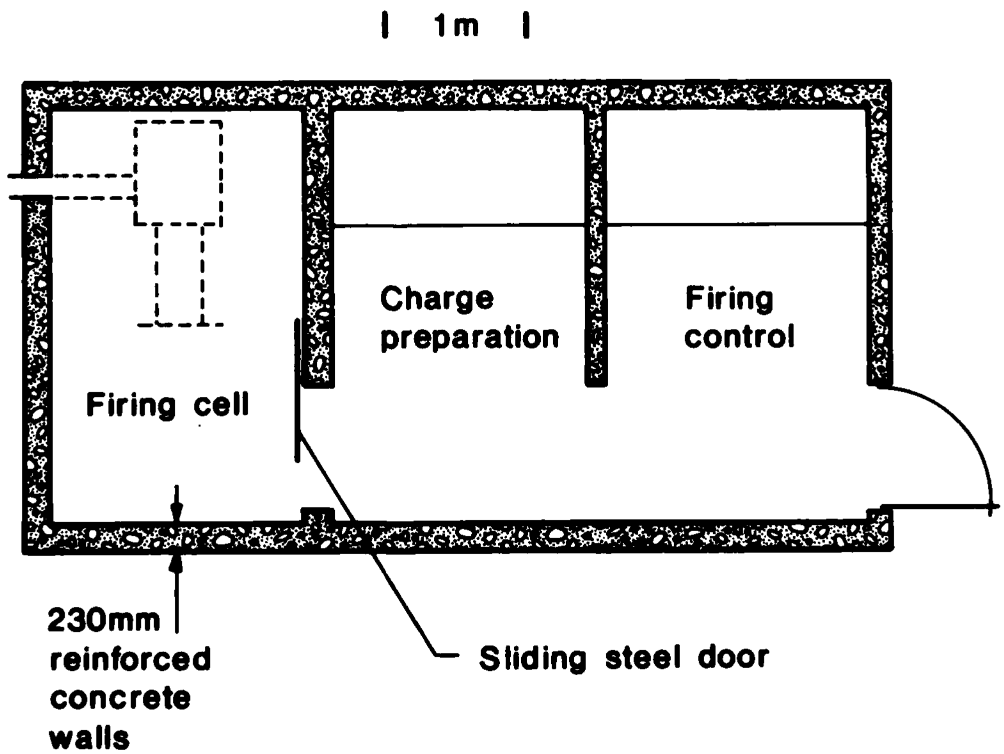


FIGURE 3. Floor plan of gap test firing facility.

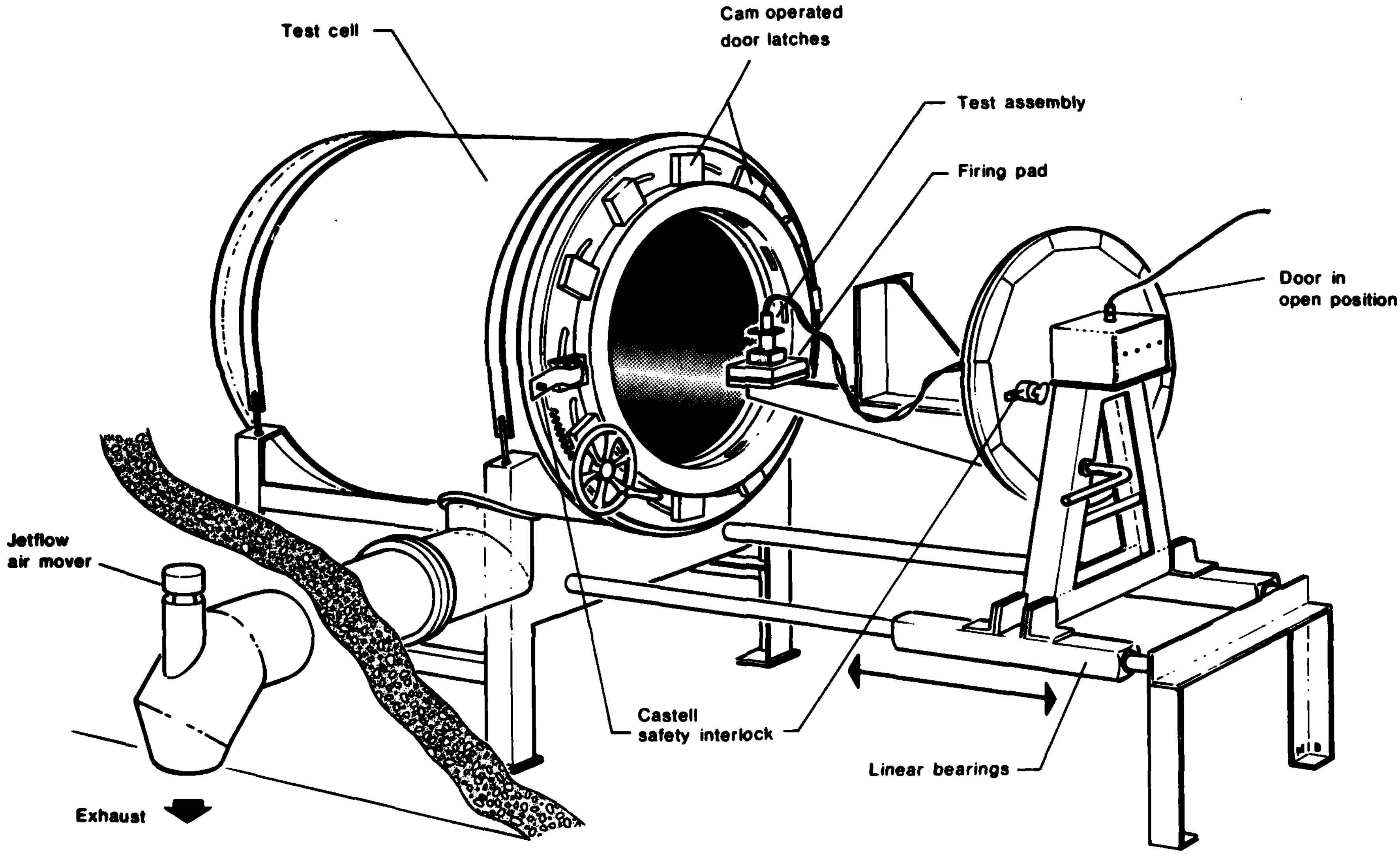


FIGURE 4. Illustration of explosive firing cell.

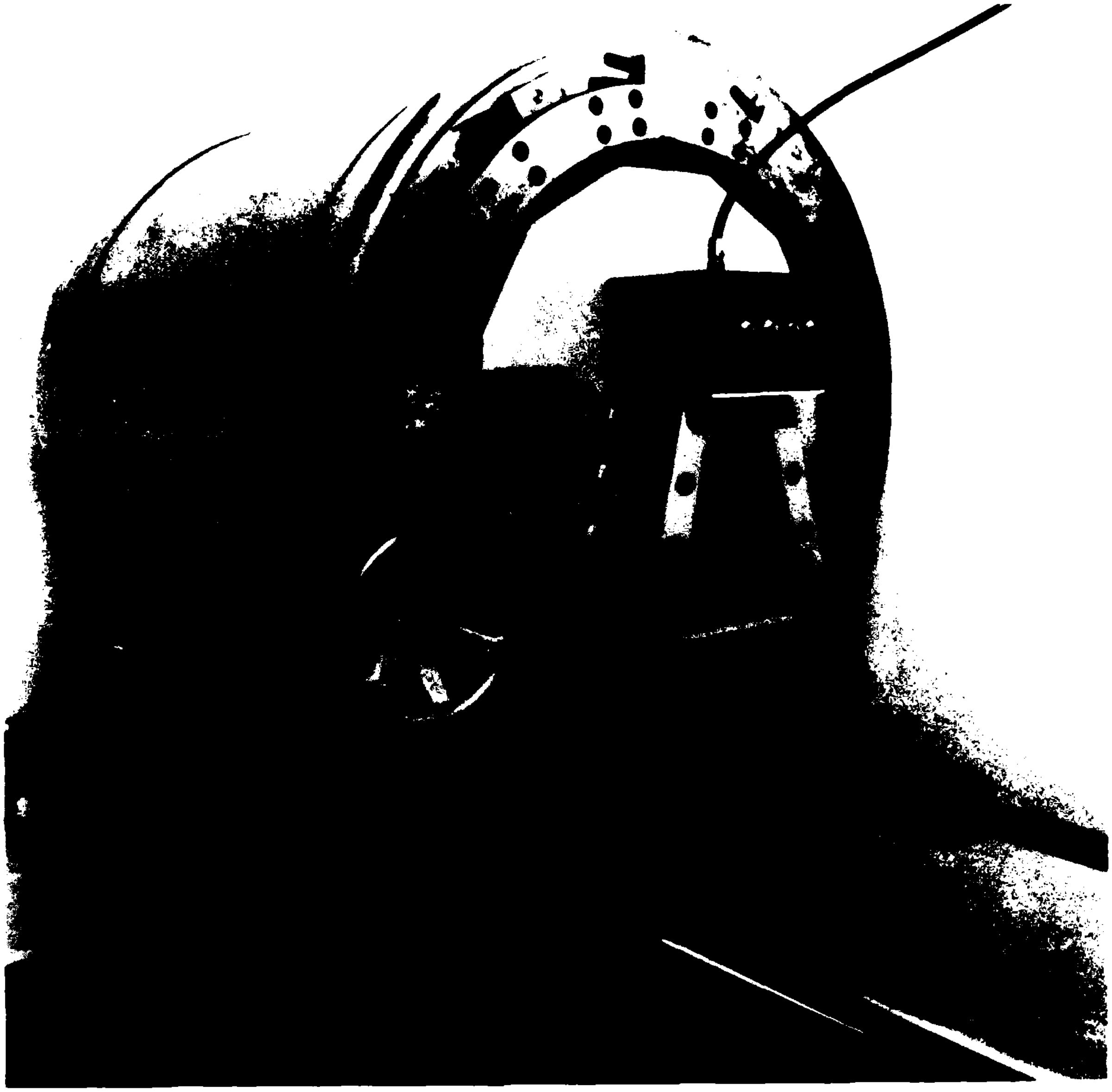


FIGURE 5. Photograph of explosive firing cell with door closed.

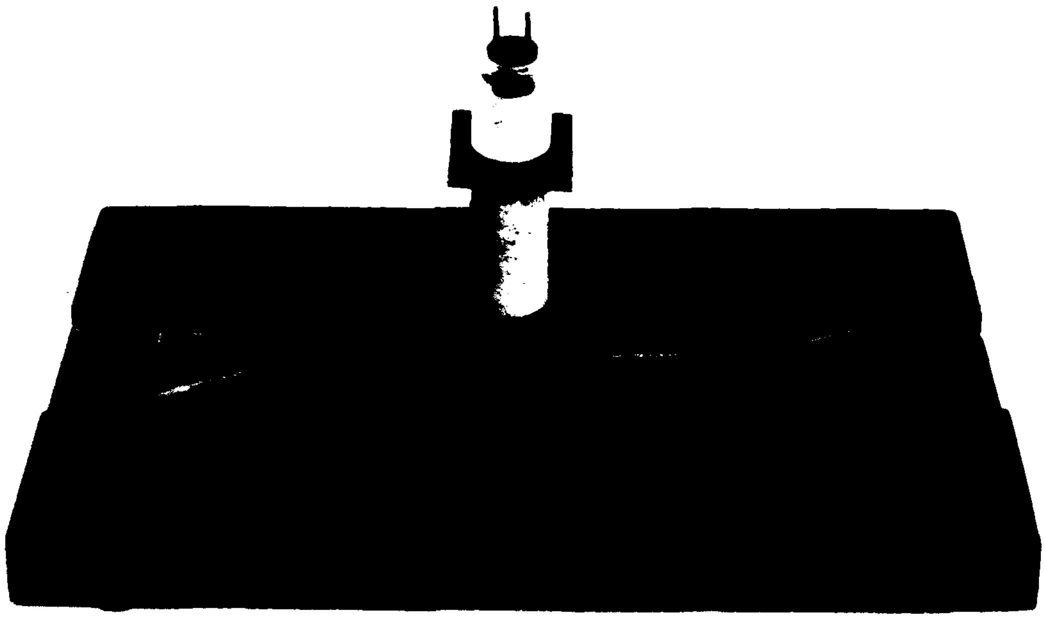


FIGURE 6. Photograph of test assembly on jig prior to positioning rubber band.

FIGURE 7. Enlarged photograph of witness block after detonation, showing top view and section through dent.

APPENDIX 1

GAP TEST ASSESSMENT OF SHOCK SENSITIVITY

Sample test results including table and graphs required for Dixon and Mood [11] statistical analysis.

GAP TEST ASSESSMENT OF SHOCK SENSITIVITY

DATE OF TEST 12-2-82	OPERATOR F. SOMODJI	TEST NO. 9/82

A. DESCRIPTION OF EXPLOSIVE MATERIAL TESTED:

TYPE	PE4	COMPOSITION	88% RDX
DETAILS OF FABRICATION			
DENSITY	1.59 Mg/m^3	ADDITIONAL INFORMATION	Lot. No. 80 Incorp. No. 690

B. TEST CONDITIONS:

		TEST TEMPERATURE	AMB
TYPE OF DONOR	SCALE 1		
BARRIER MATERIAL	BRASS	BARRIER THICKNESS INTERVAL d (mils)	2
ADDITIONAL INFORMATION			

C. TEST RESULTS: CODE: D = Detonation N.D. = Non-Detonation
t = Barrier thickness (mils)

No.	t	Result	No.	t	Result	No.	t	Result	No.	t	Result
1	20	D	13	20	D	25	24	ND	37		
2	22	D	14	22	D	26			38		
3	24	ND	15	24	ND	27			39		
4	22	ND	16	22	ND	28			40		
5	20	D	17	20	ND	29			41		
6	22	ND	18	18	D	30			42		
7	20	D	19	20	D	31			43		
8	22	ND	20	22	D	32			44		
9	20	D	21	24	ND	33			45		
10	22	ND	22	22	D	34			46		
11	20	D	23	24	ND	35			47		
12	22	ND	24	22	D	36			48		

D. RESULTS OF STATISTICAL ANALYSIS:

$m_{50\%}$	21.6	$\sigma m_{50\%}$	0.41	$L_{95\%}(m_{50\%})$	21.6 ± 0.89 = 22.56 & 20.78

GAP TEST ASSESSMENT OF SHOCK SENSITIVITY

CALCULATION SHEET FOR DIXON AND MOOD STATISTICAL ASSESSMENT

DATE 15-2-82	ASSESSOR F. SOMODJI	TEST NO. 9/82

COMMENCING AT SHOT NO. 1	c(mils) = 18	d(mils) = 2

TEST GAP THICKNESS (mils) (ASCENDING ORDER ↓)	NUMBER OF DETONATIONS (use + in eqn. 1)	NUMBER OF DETONATIONS (use − in eqn. 1)	i	n_i	in_i	i^2n_i
18 (c)	1	0	0	0	0	0
20	7	1	1	1	1	1
22	5	6	2	6	12	24
24	0	5	3	5	15	45
			4			
			5			
			6			
			7			
			8			
			9			
	TOTAL = 13	TOTAL = 12				
			Σ	12	28	70

N.B. c = smallest shim thickness used in calculations
n_i = number of detonations or non-detonations, use whichever has the smallest <u>total</u> number.

(1) $$m_{50\%} = c + d\left(\frac{\Sigma in_i}{\Sigma n_i} \pm \tfrac{1}{2}\right) = 18 + 3.\dot{6} = \underline{21.\dot{6}}$$

(2) $$M = \left(\frac{\Sigma\, i^2 n_i}{\Sigma\, n_i}\right) - \left(\frac{\Sigma\, in_i}{\Sigma\, n_i}\right)^2 = 5.8\dot{3} - 5.\dot{4} = \underline{0.3\dot{8}}$$

(3) s = <u>0.675</u> (From Dixon and Mood Table 1 and Graphs I & II)

(4) G = <u>1.060</u> (From Graphs III and IV).

(5) $\sigma = d \times s = \underline{1.35}$

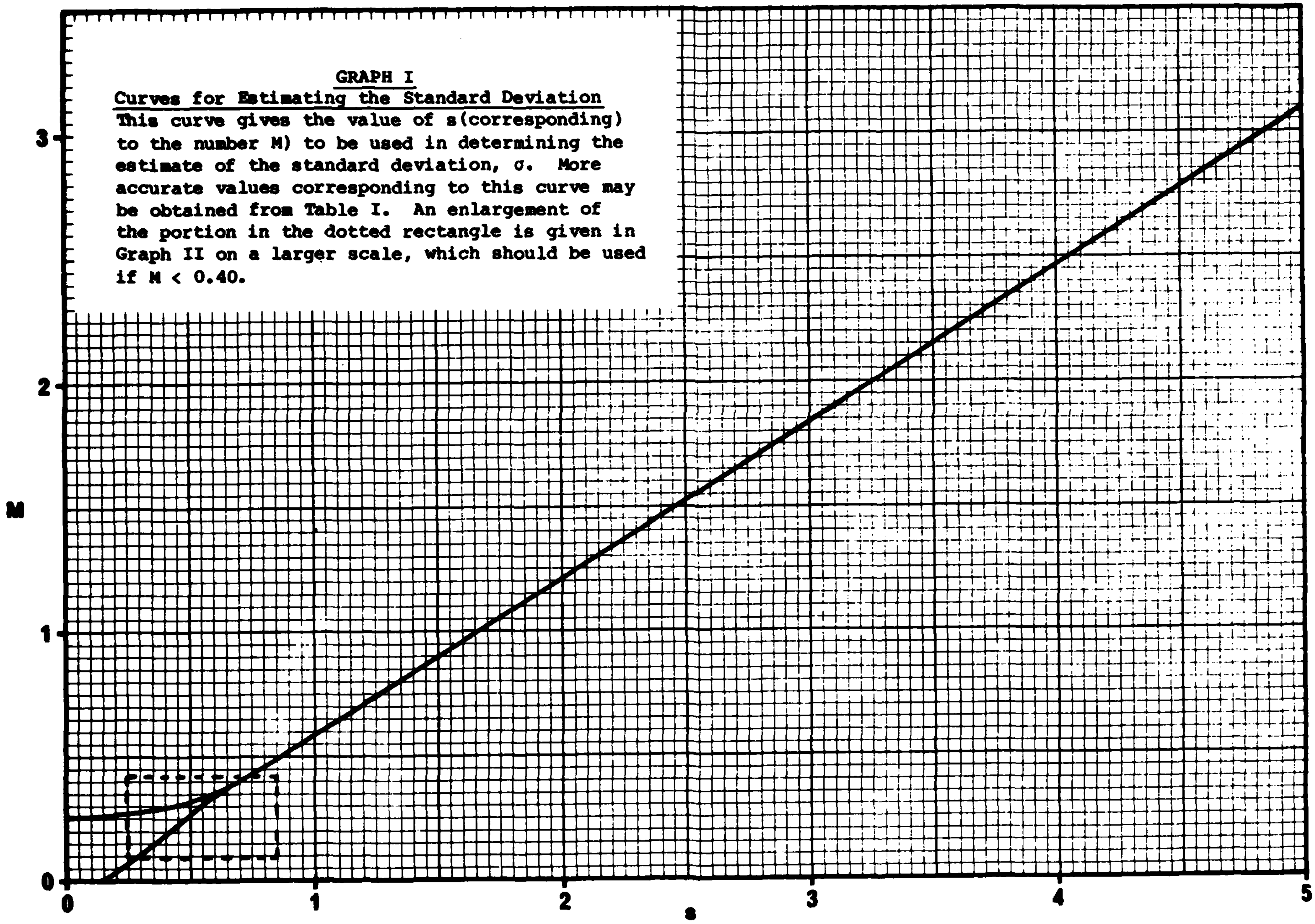
(6) $$\sigma\, m_{50\%} = \frac{\sigma \times G}{\sqrt{\Sigma n_i}} = \frac{1.35 \times 1.060}{3.464} = \underline{0.413}$$

(7) $$L_{95\%}\,(m_{50\%}) = m_{50\%} \pm 1.96\left(\frac{\Sigma n_i + 1.2}{\Sigma n_i}\right)\sigma\, m_{50\%} = \underline{21.\dot{6} \pm 0.891}$$

$$= \underline{22.558 \text{ and } 20.776}$$

TABLE I Table of s for Obtaining the Sample Standard Deviation

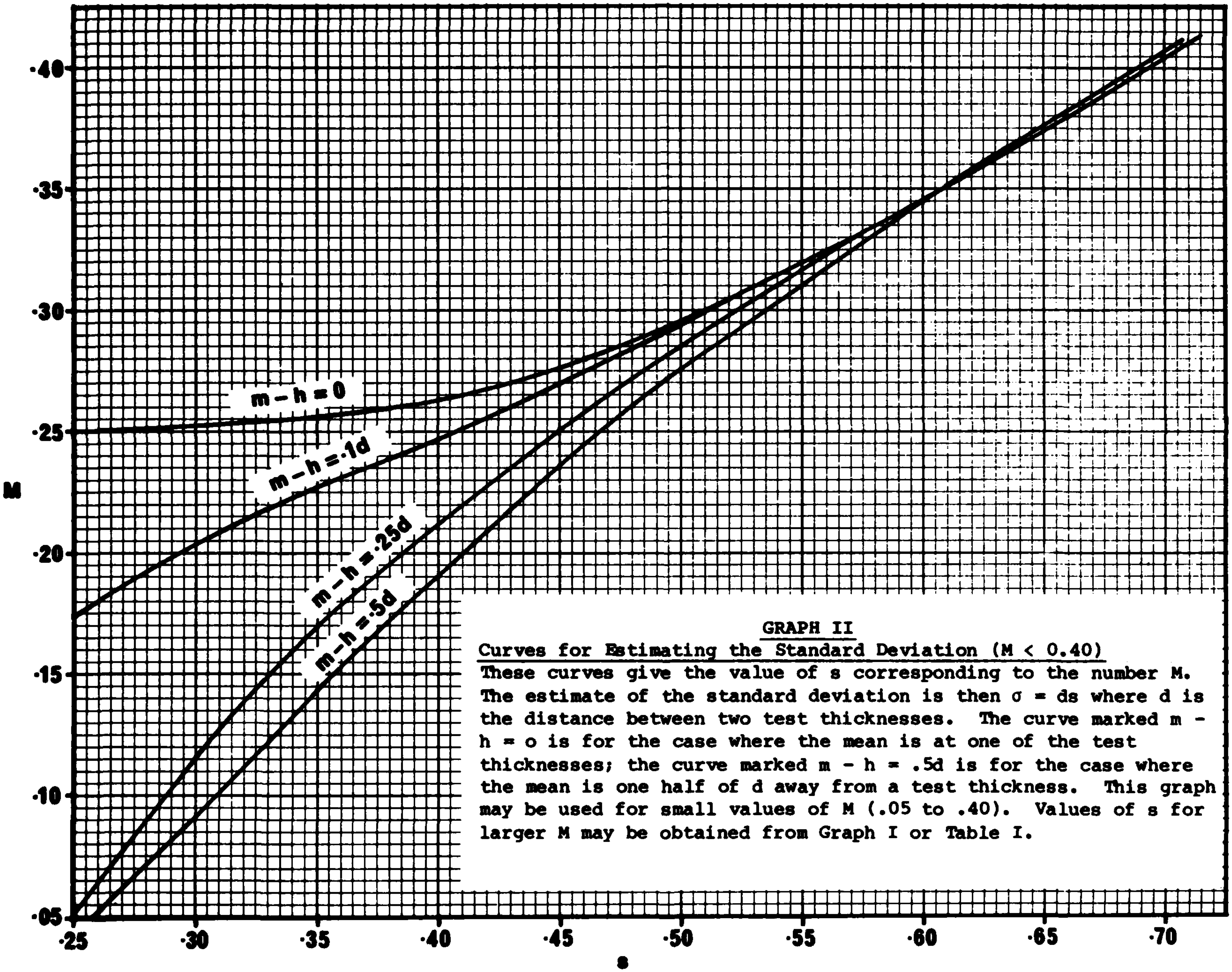
M	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.30	.5102+239	.5316+168	.5518+113	.5711+ 70	.5897+ 37	.6077+ 13	.6253- 5	.6426- 18	.6597- 28	.6765- 34
.40	.6932- 37	.7098- 39	.7263- 39	.7427- 37	.7591- 36	.7754- 33	.7917- 31	.8079- 27	.8242- 24	.8405- 22
.50	.8567- 19	.8729- 16	.8892- 14	.9054- 12	.9216- 10	.9379- 9	.9541- 7	.9703- 6	.9866- 5	1.0028- 4
.60	1.0190- 3	1.0353- 3	1.0515- 2	1.0677- 2	1.0839- 1	1.1001 0	1.1164- 1	1.1326- 1	1.1488 0	1.1650 0
.70	1.1812 0	1.1974- 1	1.2135 0	1.2297	1.2459	1.2621	1.2783	1.2944	1.3106	1.3267
.80	1.3429	1.3590	1.3752	1.3913	1.4075	1.4236	1.4397	1.4559	1.4720	1.4881
.90	1.5043	1.5204	1.5365	1.5526	1.5678	1.5848	1.6009	1.6170	1.6331	1.6492
1.00	1.6653	1.6814	1.6975	1.7135	1.7296	1.7457	1.7618	1.7779	1.7939	1.8100
1.10	1.8261	1.8422	1.8582	1.8743	1.8904	1.9064	1.9225	1.9386	1.9546	1.9707
1.20	1.9867	2.0028	2.0188	2.0349	2.0509	2.0670	2.0830	2.0991	2.1151	2.1312
1.30	2.1472	2.1633	2.1793	2.1953	2.2114	2.2274	2.2435	2.2595	2.2755	2.2916
1.40	2.3076	2.3236	2.3397	2.3557	2.3717	2.3878	2.4038	2.4198	2.4358	2.4519
1.50	2.4679	2.4839	2.4999	2.5159	2.5320	2.5480	2.5640	2.5800	2.5960	2.6121
1.60	2.6281	2.6441	2.6601	2.6761	2.6921	2.7082	2.7242	2.7402	2.7562	2.7722
1.70	2.7882	2.8042	2.8202	2.8362	2.8523	2.8683	2.8843	2.9003	2.9163	2.9323
1.80	2.9483	2.9643	2.9083	2.9963	3.0123	3.0283	3.0443	3.0603	3.0763	3.0923
1.90	3.1083	3.1243	3.1403	3.1563	3.1723	3.1883	3.2043	3.2203	3.2363	3.2523
2.00	3.2683	3.2843	3.3003	3.3163	3.3323	3.3483	3.3643	3.3803	3.3963	3.4123
2.10	3.4283	3.4443	3.4603	3.4763	3.4923	3.5083	3.5243	3.5402	3.5562	3.5722
2.20	3.5882	3.6042	3.6202	3.6362	3.6522	3.6682	3.6841	3.7001	3.7161	3.7321
2.30	3.7481	3.7641	3.7801	3.7961	3.8121	3.8280	3.8440	3.8600	3.8760	3.8920
2.40	3.9080	3.9240	3.9400	3.9560	3.9720	3.9879	4.0039	4.0199	4.0359	4.0519
2.50	4.0678	4.0838	4.0998	4.1158	4.1318	4.1477	4.1637	4.1797	4.1957	4.2117
2.60	4.2277	4.2436	4.2596	4.2756	4.2916	4.3075	4.3235	4.3395	4.3555	4.3715
2.70	4.3874	4.4034	4.4194	4.4354	4.4514	4.4673	4.4833	4.4993	4.5153	4.5313
2.80	4.5472	4.5632	4.5792	4.5952	4.6111	4.6271	6.6431	4.6591	4.6750	4.6910
2.90	4.7070	4.7230	4.7390	4.7549	4.7709	4.7869	4.8029	4.8188	4.8348	4.8508
3.00	4.8668									



GRAPH I

Curves for Estimating the Standard Deviation

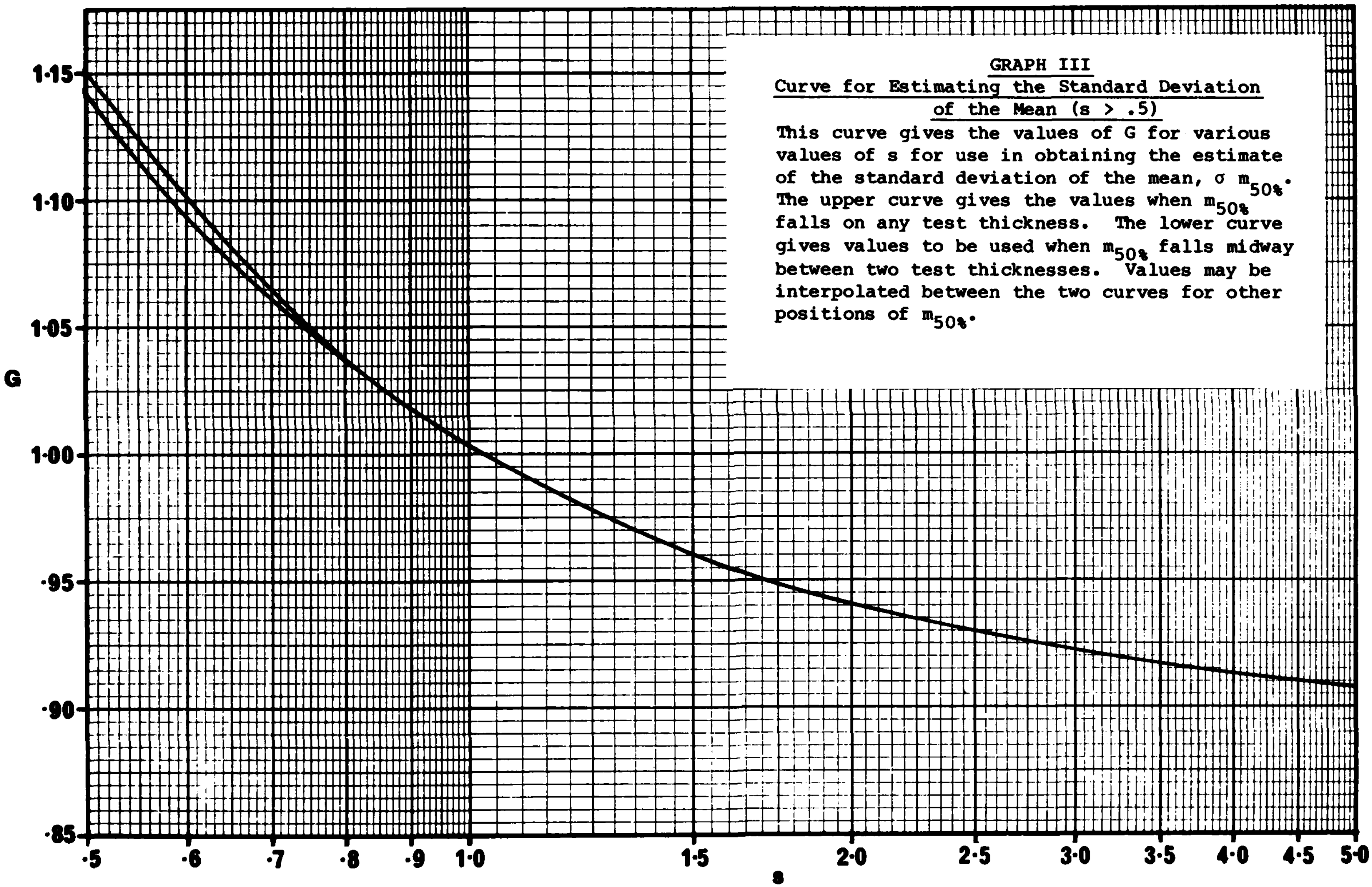
This curve gives the value of s(corresponding to the number M) to be used in determining the estimate of the standard deviation, σ. More accurate values corresponding to this curve may be obtained from Table I. An enlargement of the portion in the dotted rectangle is given in Graph II on a larger scale, which should be used if $M < 0.40$.



GRAPH II

Curves for Estimating the Standard Deviation ($M < 0.40$)

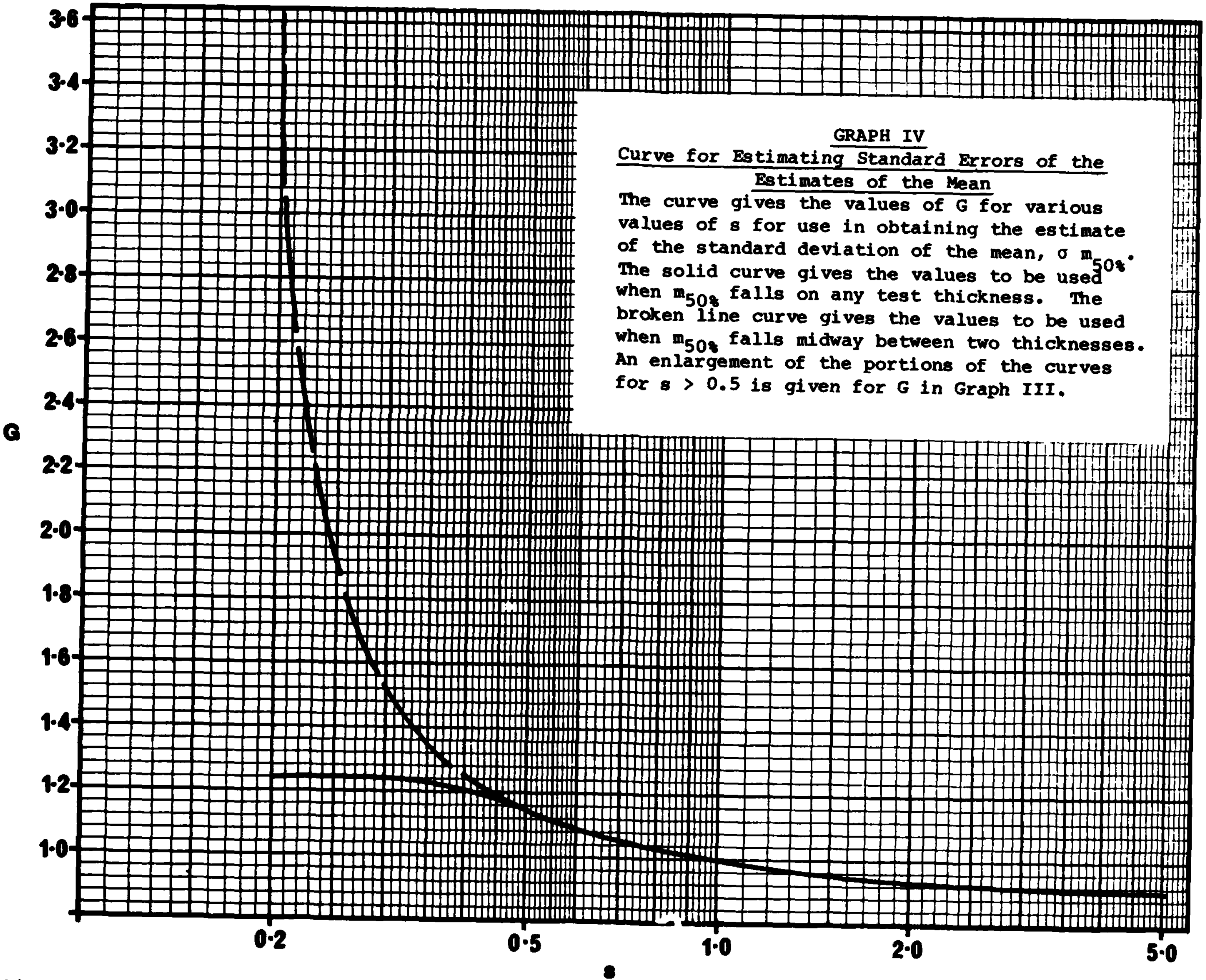
These curves give the value of s corresponding to the number M. The estimate of the standard deviation is then $\sigma = ds$ where d is the distance between two test thicknesses. The curve marked $m - h = o$ is for the case where the mean is at one of the test thicknesses; the curve marked $m - h = .5d$ is for the case where the mean is one half of d away from a test thickness. This graph may be used for small values of M (.05 to .40). Values of s for larger M may be obtained from Graph I or Table I.



GRAPH III

Curve for Estimating the Standard Deviation of the Mean ($s > .5$)

This curve gives the values of G for various values of s for use in obtaining the estimate of the standard deviation of the mean, $\sigma\ m_{50\%}$. The upper curve gives the values when $m_{50\%}$ falls on any test thickness. The lower curve gives values to be used when $m_{50\%}$ falls midway between two test thicknesses. Values may be interpolated between the two curves for other positions of $m_{50\%}$.



GRAPH IV

Curve for Estimating Standard Errors of the Estimates of the Mean

The curve gives the values of G for various values of s for use in obtaining the estimate of the standard deviation of the mean, $\sigma\, m_{50\%}$. The solid curve gives the values to be used when $m_{50\%}$ falls on any test thickness. The broken line curve gives the values to be used when $m_{50\%}$ falls midway between two thicknesses. An enlargement of the portions of the curves for s > 0.5 is given for G in Graph III.

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