Switching Notes
Note 21

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HIGH SPEED BREAKDOWN OF PRESSURISED SULPHUR HEXAFLUORIDE AND AIR IN NEARLY UNIFORM GAPS

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INTRODUCTION

This note records a short series of experiments on the pulse breakdown voltages of SF_6 and air in nearly uniform gaps. The initial motivation to start these experiments was the anomalous behaviour observed by Tommy Storr in a small pressurised SF_6 rail gap used as a switch in a 500 kV oil Blumlein generator. These results suggested that the breakdown voltage of the gap failed to increase with pressure above about 40 psig. This effect was fairly quickly traced to three different phenomena occurring in different versions of the gap. But before this had happened, a short series of tests was done with a rail gap in a 1 MV EMP generator (TOM) that was about to be delivered to the customer. These tests roughly confirmed a curve based on data obtained six years ago by Ian Smith, when he was at AWRE, for a sphere gap used in an oil Blumlein system called PLATO and showed that Tommy's gap was being influenced by other effects. Just as this position was reached and the original trouble resolved, data arrived from Ian Smith showing very large fields in a rapidly charged uniform field pressurised SF_6 gap, which had been obtained at PI. It was speculated that the effect could be due either to the rapid pulse charging of the gap or that there might be a gap length dependency of the field, the breakdown field increasing with gap length, the gap spacing being rather bigger in the PI tests than in any previous cases available.

As a suitable test bed existed in the form of the EMP generator, a rather more extensive series of tests was mounted, involving air and SF_6 in two different rail gaps, one roughly a half-scale version of the other. In addition, Tommy Storr generated some completely independent data for SF_6 with his rail gap which was now operating very satisfactorily. As an exercise in scientific archaeology, Ian's original PLATO data was excavated from the record books and reduced to maximum field values. In addition, I recalled some data with a very small rail gap which was obtained in the pre-history era before written records were invented.

It seems to me that it is worth recording this information and on the way describing the performance of an output rail gap for EMP generators, which was mildly surprising from a different point of view, that of air flashover.

BRIEF DESCRIPTION OF GAPS

PLATO GAP

This was a cylindrical gap with an ID of 4-1/2". The spherical electrodes (phosphor bronze ball bearings) had had the rear faces cut off and were situated in the cylindrical portion of the gap only. The spacing was 3.0 cm and the gap was located in between fairly extensive plates forming the transmission line, under oil. It had been operated up to 200 psig and on one momentus occasion it (or another small gap like it) had tracked, cracking the perspex pressure vessel. This would have done little damage in itself, but the 200 psi took out the face of the perspex oil container, dumping a cubic metre or two of oil on the floor. Estimation of the field enhancement factor (FEF) presents a little difficulty, as it does in all the gaps described, but it is estimated at 1.3 because of the presence of the main line electrodes, giving a uniform equivalent gap of about 2.3 cm.

WEB GAP

This is the Tommy Storr gap mentioned earlier, the generator in which it is used having been christened (or at least named) for the purposes of this note. No prizes are offered for what it stands for, the generator being 500 kV, 50 ohms, 20 ns, and contained in a box 6-1/2 x 1-1/4 x 1 feet in size. The cylindrical electrodes are 5/8" OD and are mounted along the axis of a 2" OD perspex cylindrical body. The rods have been flattened on the back slightly and the gap is again mounted under oil between the transmission line electrodes. The electrode spacing is 1.3 cm and the FEF is estimated to be 1.24, giving an effective uniform gap of 1.04 cm or thereabouts.

TOM GAPS

TOM is an EMP generator of the Marx peaking capacitor type and the low pulse charged output gaps are what were used in these experiments. JERRY, the low level pulser, had been delivered to the user some time ago. Prior to starting on the full generator, Messrs. George Herbert, Mike Hutchinson, and Denis Akers had tested some of the features of it on a half scale and for these tests they had built a "half scale" gap. This gap consisted of 5/8" cylindrical electrodes mounted inside a 2" OD perspex body. These electrodes had had approximately 1 mm removed from their inward-facing surfaces and then the cylinders contoured to give an effective radius of curvature of the order of 1.2 cm. The actual electrode separation was 1.25 cm and it is estimated the FEF was of the order of 1.20, giving a uniform field equivalent spacing of about 1.04 cm.

It was this gap which gave some interesting results as regards the flashover, so a further description of it will be given.

The one foot wide transmission line feeds which were attached to the gap were made from 3/4" wood contoured into "uniform field" profiles at the edges and wrapped in aluminium baking foil. Approximately 3 mm perspex sheet was wrapped around the lines and simplexed onto the 2" OD body of the gap. In addition, three fins of 3 mm perspex were bent and simplexed onto the body of the gap on each side of the gap. These fins stuck out 4" from the axis of the gap and were curved in the planes containing the gap axis. Figure 1 shows a sketch of the gap. In the half-scale tests the gap was taken up to about 450 kV in air, with the bottom plane of the transmission line 18" away, with no breakdowns across the gap or between the lines observed.

Subsequently the same gap was installed in TOM (which is a 2/3 MV user generator but has been tested up to a little over 1 MV) and the half-scale gap went up to a little under 800 kV in the tests described below. At this level a track occurred which flashed over the perspex wrapped feeds but punched through the base of the three fins where these were simplexed to the body. When the gap was examined, it was observed that there were some small bubbles in one of the joints and also that it was upside down. The small holes made by the track were drilled out, patches simplexed on and the gap reinstalled the right way up. Subsequently the same gap went to 800 kV without further trouble. Such a voltage on an air-insulated gap is progressive and was partly achieved because of the rapid charging in the peaking capacity circuit ($\sqrt{LC} \sim 28$ ns). The inductance of the gap, in a one foot line, is about 22 nH and in a 140 ohms transmission line would add 0.6 ns to the rise time (it was working at 100 psig SF_6). Of course the rise time of the output pulse is mainly controlled by the wave fronts rattling around across the depth and width of the line, but an 800 kV air-insulated gap with these characteristics which is simple to make is quite useful.

The full-scale TOM gap was similar in design but had a 4" OD perspex pressure vessel. The electrodes were about 50 cm over the uniform field part and were made out of 1-1/4" tube with solid end caps added at the end where the contouring was done. The physical gap was 3.05 cm but, just to make the problem of the FEF factor even more complex, brass was removed from both outwards and inwards facing surfaces of the rods. However, the field enhancement factor was estimated to be about 1.24, giving a uniform field equivalent spacing of about 2.42 cm. This factor would apply if the gap were remote from any earth plane and in practice the field is a bit crunched up against the electrode nearest the peaking capacitor. This factor has been crudely estimated and included with another factor (the prepulse, which slightly reduces the measured voltage) and this is briefly covered later.

Table I lists the relevant parameters and also gives a very crude estimate of the stressed area in cm^2, based on a standard deviation of breakdown of about ± 3 per cent. As can be appreciated from the above, the data which are used to obtain the maximum field on the electrode at breakdown are somewhat a matter of judgment, but it is felt that the equivalent uniform field gaps are good to about 5 per cent. On top of this uncertainty, of course, are the errors in measuring the breakdown voltage of the gaps. These are felt to be, again, within 5 per cent for the more recent data. This is in part confirmed by the very good agreement obtained between the breakdown fields at low pressures between the WEB and TOM, data which were obtained in completely different set-ups with different monitors, etc.

TABLE I

Gap	Electrode Shape	Diameter (in)	Operating Length (cm)	Material	Gap (cm)	Effective FEF	"Uniform" Gap Equivalent (cm)	Stressed Area $\sigma \sim 3$ % (cm^2)
PLATO	Spheres	2	-	Phosphor Bronze	3.0	1.3	2.3	~ 1
WEB	Cylinders	5/8	10	Brass	1.3	1.24	1.04	~ 10
HALF-SCALE TOM	Cylinders	5/8	25	Brass	1.25	1.20	1.04	~ 25
FULL-SCALE TOM	Cylinders	1-1/4	50	Brass	3.05	1.26	2.42	~ 100

RESULTS

PLATO GAP

The PLATO gap results show significant jitter and also the breakdown point on the charging waveform is sometimes a little obscure. However, by selection of the better data, the curve given in Figure 2 has been obtained. It should be mentioned that in Ian's original work pressures up to 300 psig were used in various gaps and with various electrode materials, so the curve given only represents a small part of his work at that time in this area. An additional point is that the values of t_{eff} used later are judged from the waveforms and may not be very accurate. However, as these numbers are taken to a low power, this factor is unlikely to have influenced the results.

WEB GAP

Tommy Storr's SF_6 data were obtained with the final electrode shapes of a short series of different forms and represent the values obtained after quite a lot of shots. Indeed, the initial curve obtained was some 10 per cent lower and some degree of conditioning occurred. The final curve given in Figure 2 therefore represents a gap conditioned by maybe a hundred or more breakdowns. The coulombs passing through the gap are a bit difficult to define exactly (there being a high speed current pulse as well as a slower ringing) but are in the range of a few millicoulombs.

TOM GAPS

The design of the peaking capacitor made it comparatively easy to change the value of this. In addition, extra inductances could be placed between the Marx and the peaking capacitor. By means of these changes, the $\sqrt{LC}$ could be varied over a factor of about 4. Breakdown values were taken at 3 values of the rise time for the small gap and for the slowest and fastest waveforms for the large gap. The monitoring point was across the peaking capacitor and this measured the voltage on the high voltage electrode of the gap to earth. Fairly low resistances were placed across the output face of the generator, but because of the capacity of the gap, a small prepulse appeared on the output side of the gap. This varied between 2 per cent and 8 per cent, depending on the rate of rise of the pulse on the gap and on which gap it was. In addition to this, the field lines were distorted towards the high voltage electrode because of the presence of the resistors across the output face and the return earthy transmission line some 24" below the gap. This effective was estimated to be some 5 per cent and was included with the effect of the prepulse when the breakdown voltages were transformed into maximum field values on the electrodes.

The actual breakdown voltages were recorded on two 'scopes of different sensitivities and rise times and the slower 'scope corrected for this effect. In general the breakdown voltages derived from the two 'scopes were in good agreement, the average deviation between them being about 2 per cent, with no particular trend apparent between them. For the small gap working with air in it, only one of the 'scopes could be used and even this one tended to give rather small deflections, hence the air breakdown values for the small gap are less accurate than the other values.

Half way through the series, the polarity of the Marx was changed and a short run done with the medium rise time pulse and the half scale gap. The results showed no polarity effect apparent for the SF_6 data but did disclose a polarity effect for the air data. This effect was of the order of 10 per cent for 40 psig and decreased to about 3 per cent for 80 psig. The direction of the effect was that the positive electrode had the bigger strength. This at first sight was surprising; however, some fast edge plane work done recently shows that for small pressures the positive edge is stronger. If a differential relationship is inferred from the integral edge plane breakdown data, this does suggest that any streamers starting from positive whiskers will take longer to grow out from the electrode and that as pressurisation takes place, this effect should reverse. It should also be weakly gap length dependent.

Returning to SF_6 results, a weekend intervened in the two days of measurement and on the Monday the jitter of the SF_6 gap was seen to be much higher than it had been on the preceding working day. It was of the order of 6 per cent, whereas in general the jitter was 3 per cent or less, apart from an occasional drop out which was ignored in taking the data. A check was made that it was not the SF_6 flow rate and after perhaps 20 shots or so it seemed to disappear. The SF_6 data at the higher pressures for the medium rise time case half scale gap are maybe a little too low because of this effect. The runs were made alternately with air and with SF_6 and no very large number of shots was taken with each run,. the total number in a run with one gas being of the order of 30, this number including a few initial shots after the gas had been changed which were not recorded. Figure 2 gives the breakdown voltages (uncorrected for prepulse and field crunching) for SF_6 and Figure 3 gives the breakdown data for air (again uncorrected) for the high voltage electrode being negative. The charge carried by the gaps was again in the range of a few millicoulombs.

In the case of the SF_6 measurements at atmospheric pressure, there were considerable signs of fizzle, there not being a clean transition to full conduction in the switch. This had also been observed as an effect on the rise time of the output pulse in other experiments. However, by the time the gap was pressurised to some 15 psig, the fizzle had largely disappeared. The transition to significant fizzle conditions was not a clear-cut one, but appeared to happen around the same pressure for both gaps for all rates of rise of the pulse, over the range examined.

BREAKDOWN FIELDS

Using the data in Table I and in Figures 2 and 3, the maximum breakdown fields for both SF_6 and air were calculated and these results are shown in Figures 4 and 5.

The data for SF_6 from the half and full scale agree very nicely where the data overlaps and shows no signs of a gap length dependency. However, there is significant evidence of a time dependency of the breakdown field. The data from PLATO and WEB are in quite reasonable agreement with those TOM results obtained with the slow rate of rise of the pulse.

In the case of air (Figure 5), there is again evidence of time dependency and also some gap length dependency as well.

Considering first the time dependency, I resort to the well-tried fudge of a one-sixth power. I can plead very little rationale for this, except that the point and edge plane breakdown data fits this as well as any other power and Laird Bradley at Sandia, Albuquerque, has found a similar dependency for a pulse charged uniform field gap working in nitrogen in a particular regime. Table II lists the $\sqrt{LC}$ values for the systems and also the old t_{eff} (full time width at 63 per cent of peak) and the value that should perhaps more rigorously be used if the time dependency is one-sixth, that of the full time width at 89 per cent of peak ($t_{89\%}$). The effective time, of course, depends on the point on the rising waveform at which it was arranged in the tests that the gap would fire and is not directly proportional to $\sqrt{LC}$. Also given is a relative time to the one-sixth power. If the parameter being used is $t_{89\%}$, then this time is 10 ns; if the old t_{eff} is being used, the reference time is 30 ns.

TABLE II (All times in ns)

	$\sqrt{LC}$	$t_{63\%}$	$t_{89\%}$	$(\text{relative } t)^{1/6}$
PLATO	~220	~100	~40	1.26
WEB	100	75	25	1.17
TOM Slow	103	37	13	1.05
Medium	50	21	7	0.97
Fast	28	10	3.5	0.84

Base time for 63 per cent 30 ns
for 89 per cent 10 ns

The results for SF_6 are given in Figure 6 and the data for the two TOM gap tests fall on essentially the same line, within a percent or so. That for the WEB tests has a closely similar value at low pressures, but has a steeper slope. The PLATO data is quite similar at low pressures but is significantly higher than the TOM data and this would still be the case if the data were corrected to be the same at 20 psig. This is tempting to do for two possible reasons, one of which is that the time dependency may begin to disappear around the 100 ns time range, and the other is that the volt may have devalued some 10 per cent since 6 years ago. However, the differences are within any accuracy expected from the basic data and the uncertainties connected with the determination of the FEF factors, etc.

The air results corrected, for a one-sixth time dependency, are shown in Figure 7. The agreement after correction is not quite as good as in the SF_6 case, where it was excellent. Even so, the large gap data (which is rather more accurate than the half scale tests, as was mentioned earlier in the note) are brought into reasonable line. In addition there is a difference between the averaged data for the two gaps, which is essentially constant at a ratio of 1.20, the larger gap holding more field.

DISCURSIVE RAMBLE OVER THE RESULTS

It is amusing to note that when this series was mounted, while it was hoped to find a length dependency for the SF_6 breakdown field, none was found, whereas for the air case, where none was needed, it was found. A time dependency for SF_6 breakdown was found but it is a fairly weak one, and certainly not enough to account for the very high stresses mentioned by Ian. However, it is felt that Figure 6 gives some clues as to how these could come about. Firstly, it is necessary to dispose of a previous explanation. This was advanced seven years or so ago, when the earliest pressurised SF_6 measurements were made. I had predicted that fields of more than 1 MV/cm would be easily obtainable when pulse charged SF_6 gaps were used. This was based on consideration of the factors I believed to be responsible for the failure of DC charged gaps to have a more or less linear relation between gas density and breakdown voltage. All of these seemed to be slow acting effects and hence should not have time to occur in pulse charged gaps. When I failed to obtain the gradients I had so blandly predicted, I retreated behind the observation that as the pressure increased to around 100 psig, the jitter of the very small test gaps I was using became large, $\sigma \sim 10$ per cent or more, and at the same time the breakdown voltage/density curve became very decidedly non-linear. This I claimed was what was causing the perverse behaviour of nature in failing to agree with my prognostications. Thus if one made many measurements, a few would be up on the more or less linear relation. Also if one could reduce the jitter, one would easily get to 1 MV/cm or more. Seven years later, that explanation looks as sick as the earlier one, since in these tests the TOM gap showed 3 per cent jitter or less up to the highest pressures used.

The explanation I now favour is the simple one of conditioning. Tommy's gap showed significant signs of conditioning and after a couple of hundred shots or so gave a much more linear dependency between breakdown field and density and, indeed, if extrapolated in a realistically slightly curved way, hits 1 MV/cm at about 100 psig. Table I lists the approximate stressed area and it is seen that the large TOM rail gap has ten times the area of the WEB gap. Thus to condition it to the extent that Tommy's gap was, it would have been necessary to fire a thousand and more shots. The size of defects one is trying to remove can be estimated very crudely as being comparable to the Townsend avalanche, which is of the order of 3.10^{-3} cm. Certainly in the large rail gaps used here, the existence of thousands of such projections in the highly stressed area is only too likely, as the electrodes were not polished or finely finished in any way. On this picture the jitter could be low after the first 10 or 20 shots and stay low as the conditioning slowly raised the mean breakdown field. For this assumed low σ conditioning to occur, firstly a fairly large area gap will be needed and in addition it would need to be rapidly pulse charged. If the TOM rail gap were very much more slowly charged, the channels instead of taking the shortest way across the gap, would be expected to begin to zigzag and to take longer paths; hence the jitter would be expected to increase considerably and the breakdown voltage at high pressures drop.

This picture of conditioning is supported by the PLATO results, where phosphor-bronze ball bearings were used. The stressed area was small and initially highly polished and the best curve lies quite a bit higher than the brass TOM results. However, in the PLATO tests the gap carried large currents and significant deconditioning would also be expected to take place. Certainly the scatter of results in the PLATO tests was much bigger than in the TOM tests. It is quite likely the charge carried in typical EMP generators is of about the right order to condition without creating too much in the way of secondary defects or whiskers. It should also be mentioned that the orientation of the gap might be important: fortunately most such gaps are likely to be mounted so that the debris falls off the electrodes.

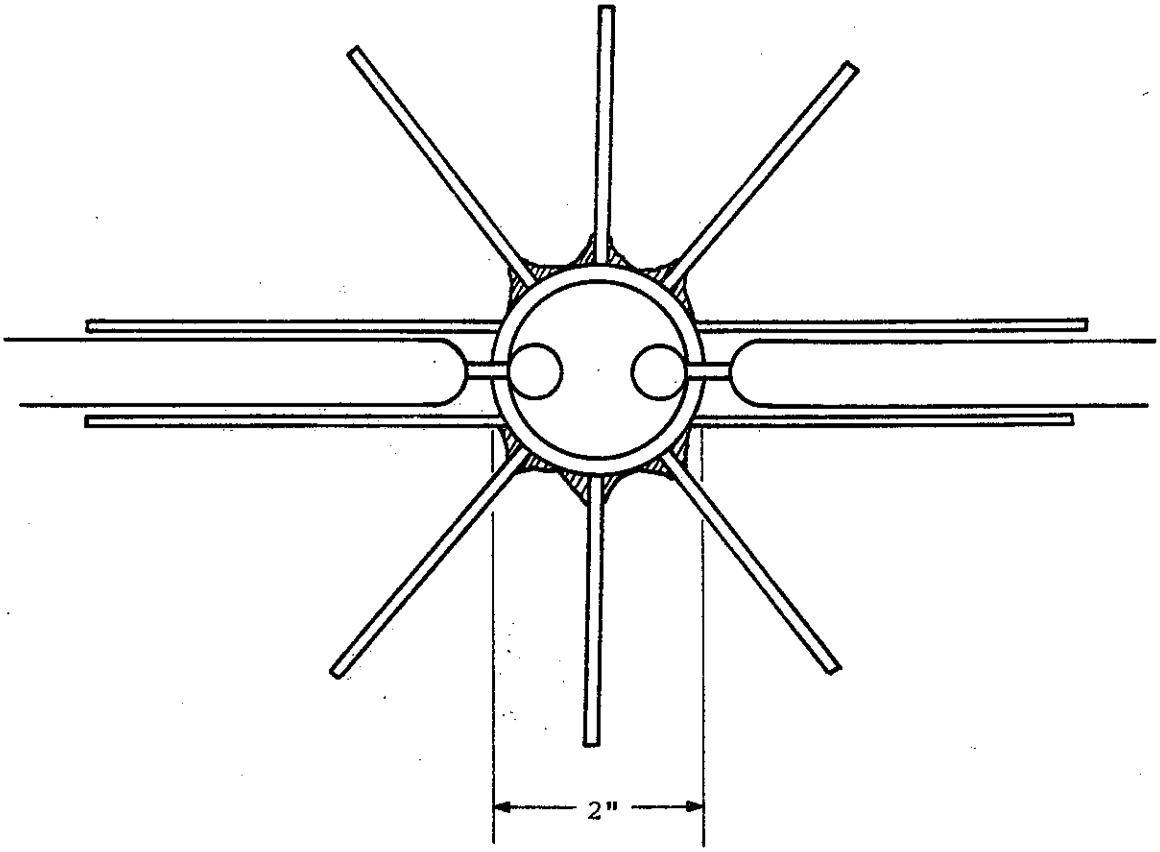
While brass is a very good electrode material to use in DC charged pressurised high coulomb SF_6 gaps, there is no particular reason why it should be a good material for EMP output gaps. One would expect that a rather harder metal would be better, providing that it could take a good polish and that preferably it passivated when sparked in SF_6. The first property is easy to judge: the second can probably best be studied in intelligently guided tests. Unfortunately in the TOM tests the gaps were totally sealed ones, so they could not easily be opened and the electrodes removed and polished. Thus we were unable to check the above speculations in the couple of days we had available.

With regard to the air gaps, on a streamer transit picture, the larger gap would be expected to break at a higher field, but calculations suggest the effect is a few percent, not the 20 per cent found. (Similar calculations for pressurised SF_6 suggest tenths of a percent). Thus while the general gap length dependency of the breakdown field for pressurised air gaps and the small observed polarity effect are reasonable, the magnitude of the effect seems to be too large. However, further fiddling of the numbers might force agreement, but I have not had time to go into it properly yet.

ACKNOWLEDGMENTS

I should first absolve Messrs. Smith, Storr, Herbert, Hutchinson and Akers of all responsibility for most of the above. While they directly or indirectly provided much of the data, they are otherwise entirely blameless.

I would also like to acknowledge most warmly the very able and pleasant assistance of Mr. Graham Lovelock of AAEE, Boscombe Down, who, after suffering me for three months, still had enough uncurdled milk of human kindness left to slog through a hectic series of measurements with me in a conscientious and cheerful way. Without him, the measurements would not have been started, let alone completed.



Sketch 1/2 scale

1/2 scale Tom gap, 800 KV in air FIGURE 1

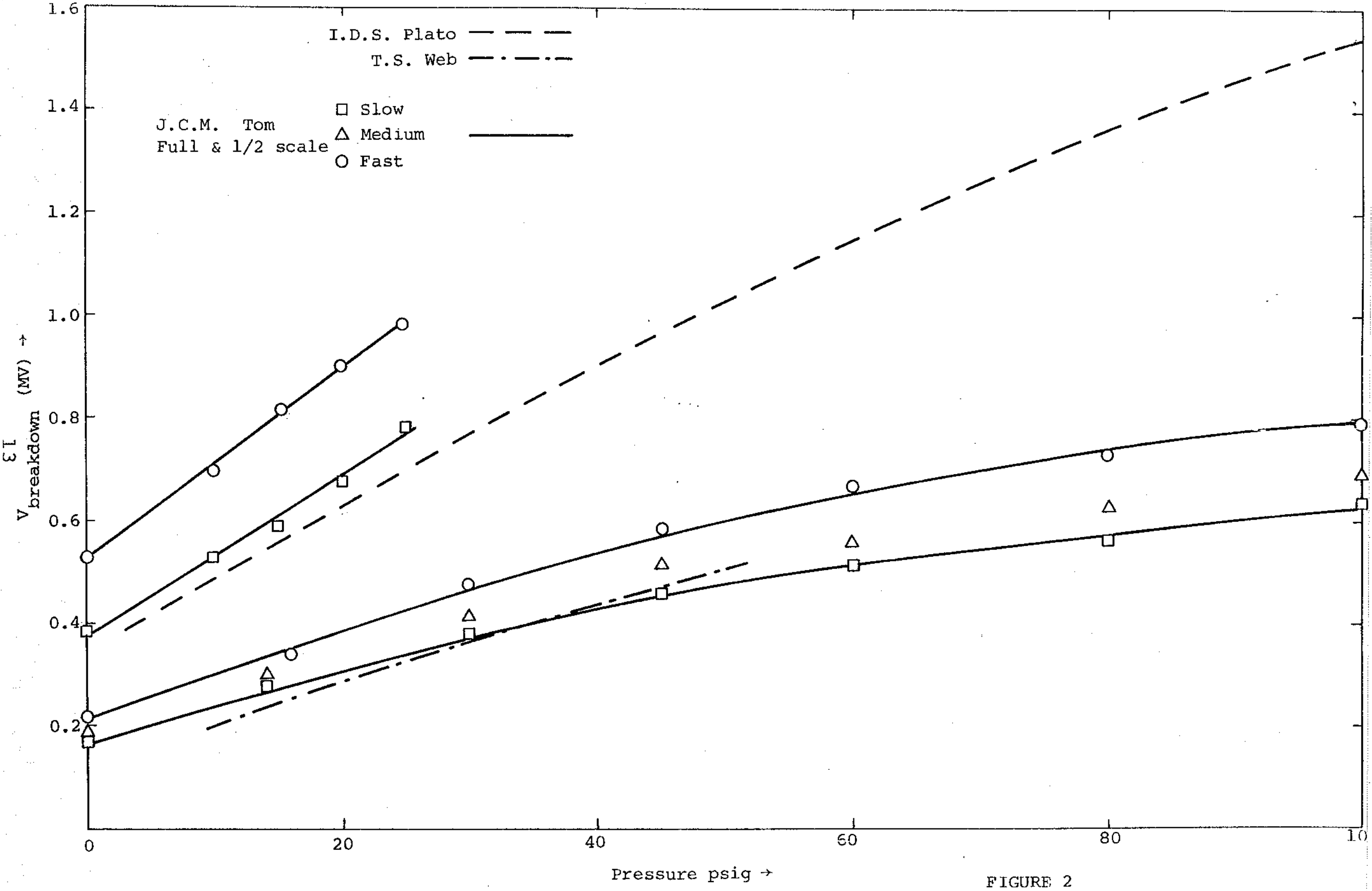

I.D.S. Plato
T.S. Web
J.C.M. Tom
Full & 1/2 scale
Slow
Medium
Fast
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$V_{breakdown}$ (MV) →
0
20
40
60
80
10
Pressure psig →

FIGURE 2

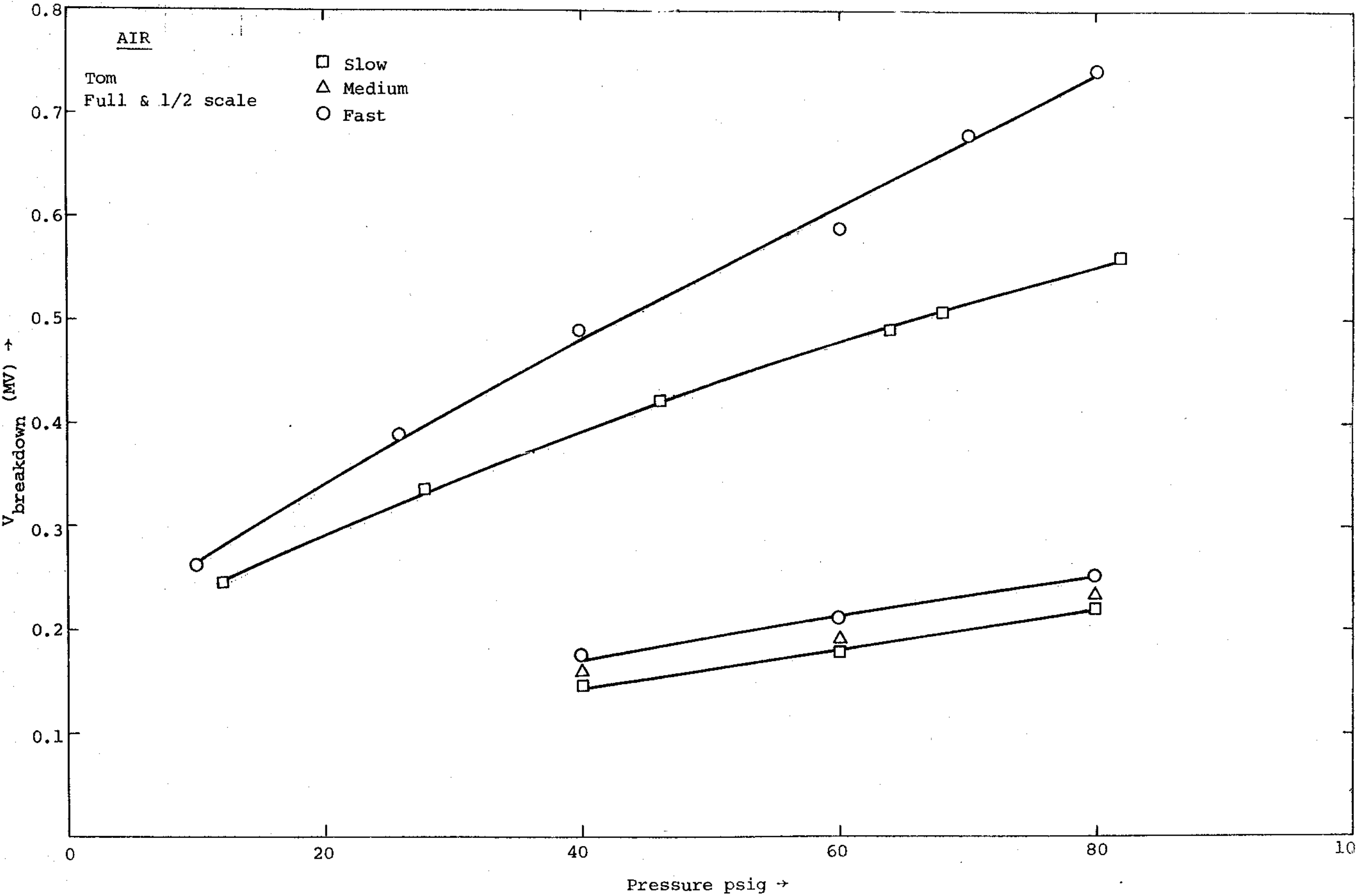
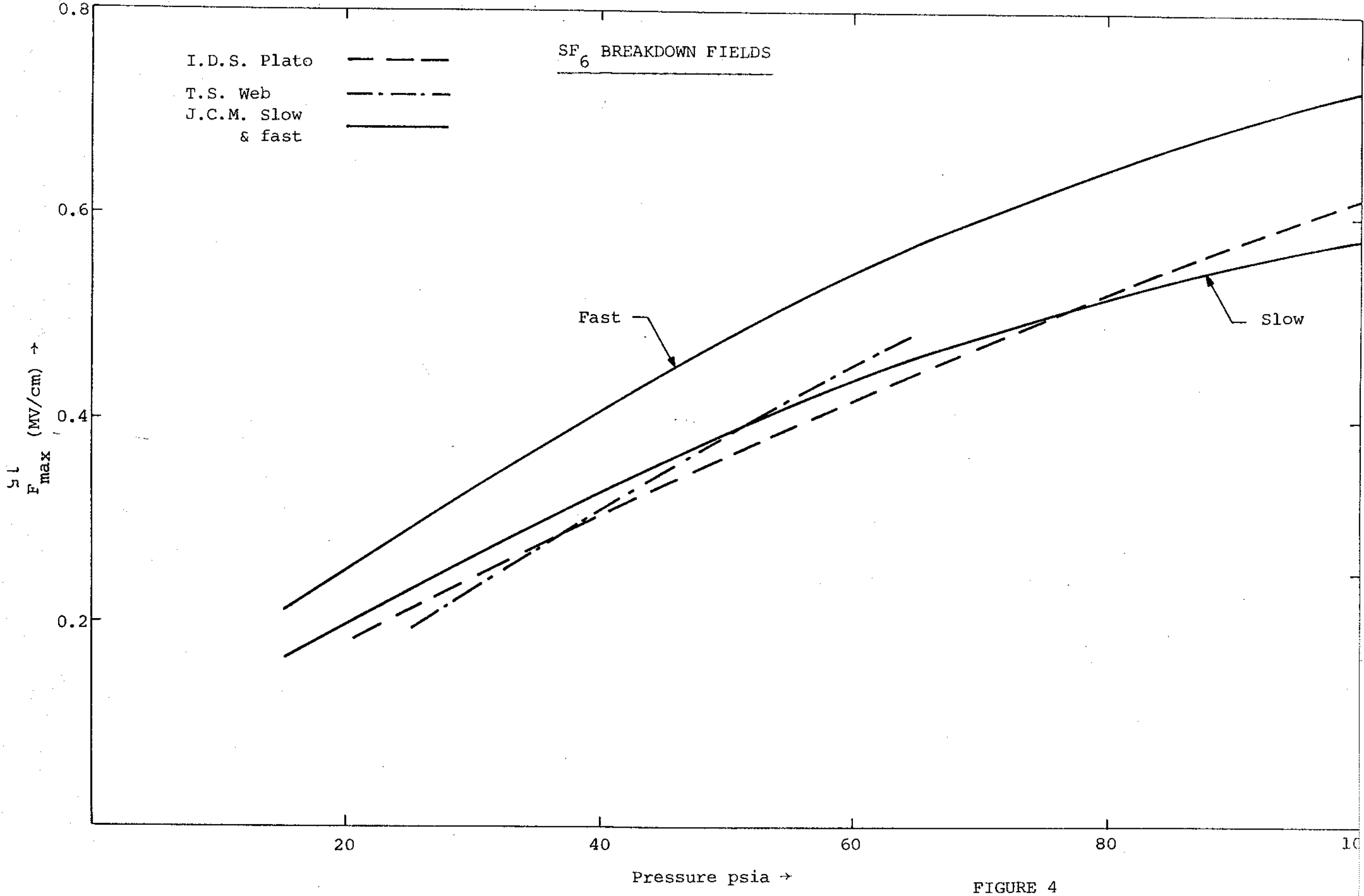

AIR
Tom
Full & 1/2 scale
□ Slow
△ Medium
○ Fast
$V_{breakdown}$ (MV) →
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
40
60
80
10
Pressure psig →

FIGURE 3



SF_6 BREAKDOWN FIELDS
I.D.S. Plato
T.S. Web
J.C.M. Slow & fast
Fast
Slow
0.8
0.6
0.4
0.2
F_{max} (MV/cm) →
20
40
60
80
10
Pressure psia →

FIGURE 4

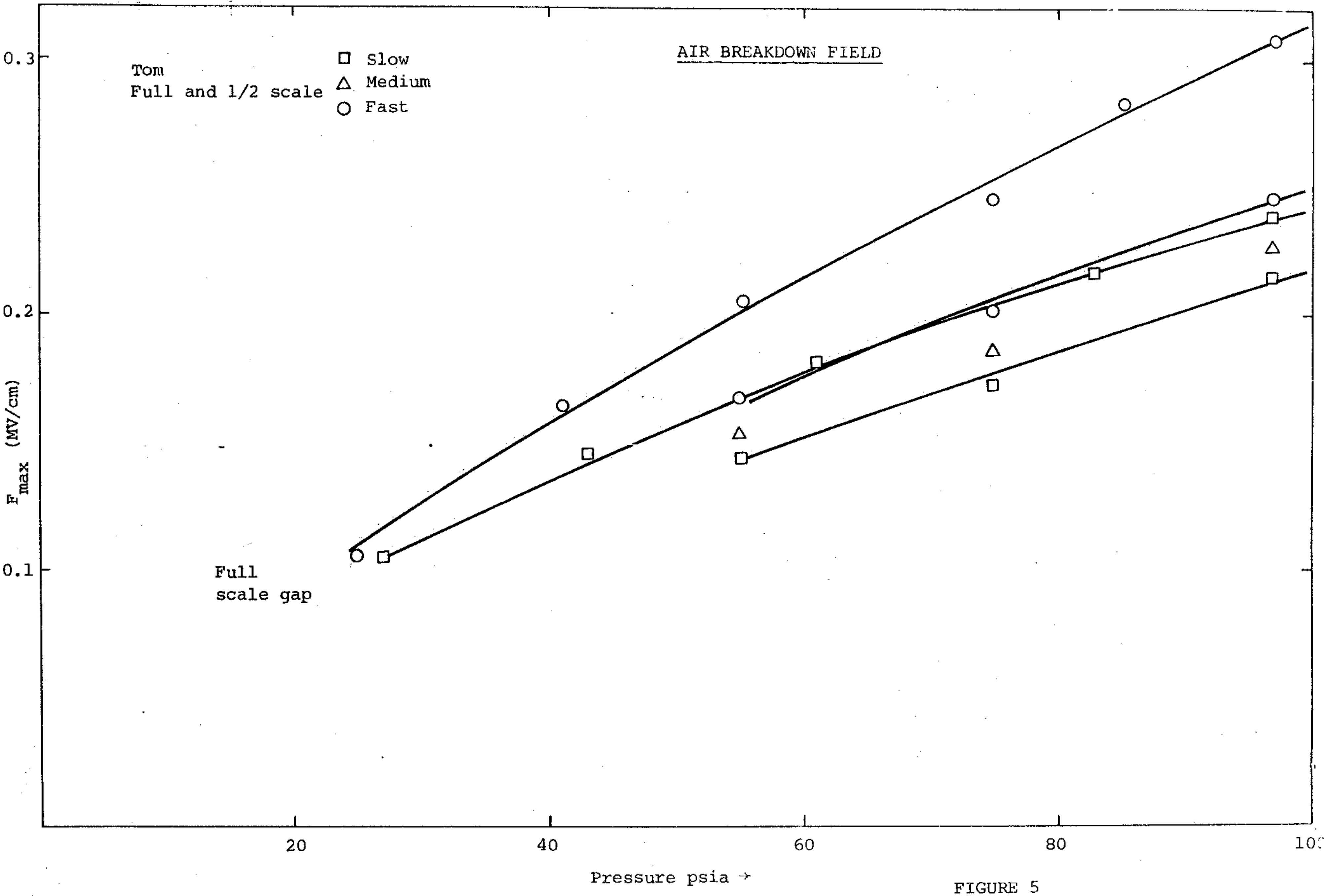

AIR BREAKDOWN FIELD
Tom
Full and 1/2 scale
□ Slow
△ Medium
○ Fast
Full
scale gap
F_{max} (MV/cm)
0.3
0.2
0.1
20
40
60
80
10
Pressure psia →

FIGURE 5

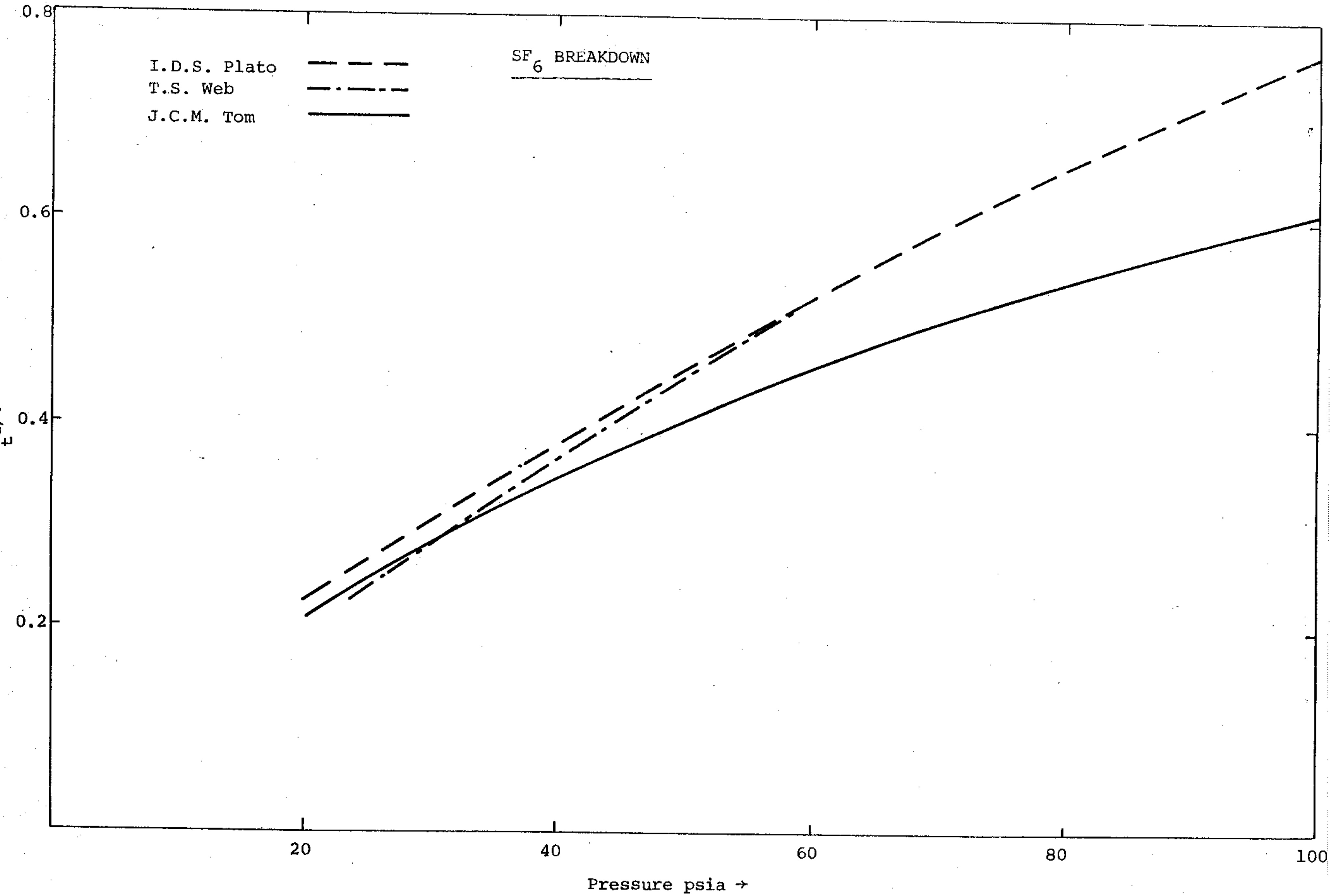

I.D.S. Plato
T.S. Web
J.C.M. Tom
SF_6 BREAKDOWN
$t^{1/6}$
0.8
0.6
0.4
0.2
20
40
60
80
100
Pressure psia →

FIGURE 6

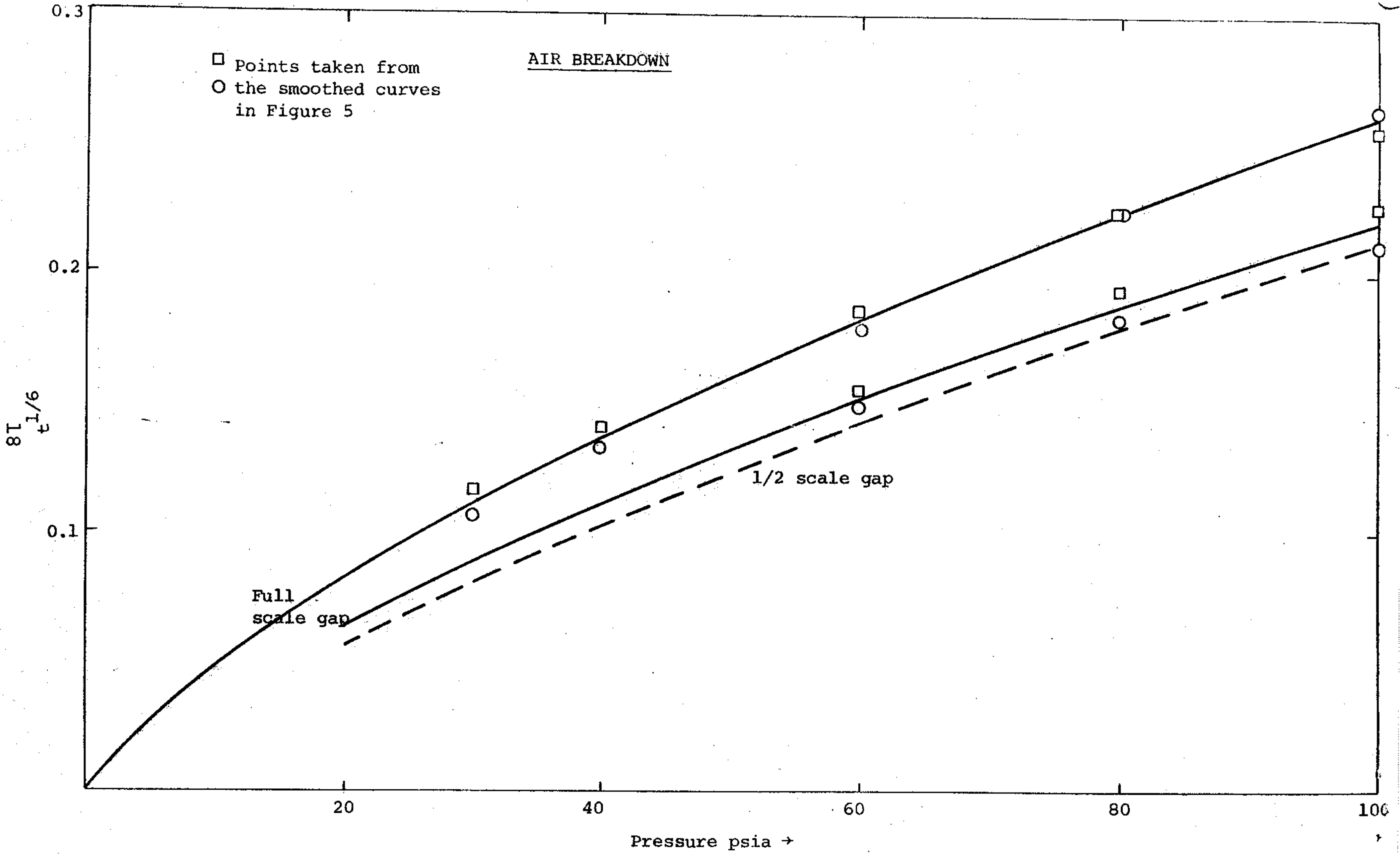

AIR BREAKDOWN
□ Points taken from
○ the smoothed curves
in Figure 5
0.3
0.2
0.1
18
$t^{1/6}$
Full scale gap
1/2 scale gap
20
40
60
80
100
Pressure psia →

FIGURE 7