

Flammable Solids & Dusts

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DUST EXPLOSION PROTECTION IN LINKED VESSELS: CONTAINMENT AND VENTING

by P Holbrow*, G A Lunn*, A Tyldesley**

*Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK, SK17 9JN

**Health and Safety Executive, Division of Science and Technology, Magdalen House, Stanley Precinct, Bootle, Merseyside, UK, L20 3QZ

Introduction

The risk of a Dust explosion is difficult to avoid in processes where combustible powders and dusts are handled. Many fine materials, eg coal, wood, flour, starch, sugar, rubber, plastics, some metals, pharmaceuticals, etc can explode once they are dispersed in air as a cloud with a suitable concentration and when an effective ignition source is present.

Dust explosions cause a rapid increase in pressure when confined in vessels or other process plant. Either the plant must be dealt with enough strength to contain the explosion and to prevent entirely the escape of any material, even when the explosion is allowed to run its full course, or some other means of protection, such as venting or suppression, must be applied.

Guidance on the application of protection techniques is published in a variety of sources, but usually applies to isolated vessels. In industry, however, plant items are connected by pipelines or conveyors and an explosion may propagate from one vessel to another, causing a secondary explosion. The conditions under which this secondary explosion takes place are generally unknown, but there is enough evidence to show that in some circumstances there can be a significant increase in the rate of combustion and violence of the explosion, and a significant increase in the explosion pressures.

The British Materials Handling Board (BMHB) has sponsored a project with the Health and Safety Executive to investigate the behaviour of dust explosions in systems of connected vessels. The main purpose of the project has been to measure the pressure changes that occur when a dust explosion is ignited in one vessel, and the flame transmits into the other. The aim has been to provide industry with guidance as to the conditions in which excessive explosion pressures may be generated in contained plant, and when and to what degree, additional venting is required on vented plant. The guidance derived from the experimental program is described in this paper.

General

Containment

Containment is used when hazard quantification indicates that an emission could present an unacceptable risk, but it may still be a valid option even when this is not so. For instance, it is often used to protect plant operating at sub-atmospheric pressure, eg vacuum dryers, and is often a suitable option for mills which, when of small volume, can be built with enough strength

to withstand maximum explosion pressures without excessive cost. Increasingly, however, this technique is being used on larger items of plant.

Practical application of containment depends on a knowledge of the maximum explosion pressure generated by the dust explosion. The maximum explosion pressure, P_{max} , can be measured in standard tests, using an apparatus such as the 20 l-sphere. P_{max} is usually measured from an initial pressure of 1 bar a. In single vessels, depending on the process conditions, the maximum pressures are usually in the range 7 - 10 times the operating pressure.

Industrial plant can then be designed to withstand the maximum explosion pressure, P_{max} without rupture. Because of its insensitivity to vessel size, the maximum pressure measured in the small-scale tests can be used to estimate directly the maximum explosion pressure that a single vessel must withstand.

It is, then, not difficult to estimate or measure directly the maximum enclosed explosion pressure in a single vessel, but with more complex configurations this is not possible. With multi-volumes or long ducts, pressure-piling effects can lead to pressures well in excess of those expected in an explosion at ambient pressure.

Pressure-piling occurs when an unburned explosible dust cloud is compressed in one part of a plant by an oncoming explosion in another. When this pre-compressed dust cloud is ignited the explosion begins at an above ambient pressure and the resulting maximum pressure is correspondingly higher. The classic case is transmission of an explosion from a large vessel into a much smaller one.

If dust-handling plant does consist of several connected items of equipment consideration must be given to isolating the various units to prevent transmission of flame or other ignition sources, to strengthening the plant to cope with pressure-piling effects and to increase the level of explosion protection.

Explosion Venting

There are a number of accepted methods for calculating dust explosion vent areas, in single vessels. They are often easy to use and require only a minimal amount of information - the volume of the vessel, the strength of the vessel, the explosibility rating of the dust, and the opening pressure of the vent closure.

Often, the calculated value of the vent area errs on the conservative side: the vent is larger than is strictly necessary to protect the plant from the real explosions likely to occur inside it. However, in linked vessels, the behaviour of the flame and subsequent increases in the rate of combustion may render ineffective venting arrangements that are more than adequate in a single vessel.

The reasons from this increase in the rate of combustion are the generation of turbulence as the explosion passes through the interconnecting pipe and the entry into the second vessel of a relatively large jet flame ignition source.

The practical result of these effects is that the explosion in the second vessel can be much faster than an explosion in an isolated vessel of the same design, and consequently, the rate of pressure rise, (dP/dt) , will be much greater.

The rate of pressure rise is the important explosion characteristic determining the venting requirements, and increased explosion violence will mean an increase in these requirements if the plant is to remain safe.

Guidance

Containment

General

The guidance is based on a simple mathematical model of pressure-piling behaviour described in **reference [1]**, and the results of the experimental programme.

Figure 1 compares calculations from the model analysis and pressure measurements from the series of experimental trials.

The analysis produces the Calculated Maximum Possible Explosion Pressure in the linked vessel system, and the experimental results are presented in terms of the maximum explosion pressure measured in the system. The volume ratio V_2/V_1 is calculated by taking V_2 as the volume of Vessel 2 and V_1 as the volume of Vessel 1 plus the volume of the interconnecting pipe. Vessel 1 is where the primary ignition takes place.

It is clear from the pressure measurements that the maximum explosion pressure falls when the diameter of the interconnecting pipe increases. This is because back-venting of the secondary explosion is more effective when the pipe diameter is greater.

The guidance gives estimations of the explosion pressures which linked, contained vessels should be designed to withstand. The highest pressures are 'worst-case' estimations; the analysis assumes slow transmission of the explosion. In practice, these conditions are not met because the speed of actual explosions is higher than assumed, and because of the back-venting effect. The back-venting effect is, however, taken into account in the guidance on the basis of the measured pressures. The K_{st} value is not a factor in this guidance.

Notes for Guidance

- 1) A major problem is that it is rarely possible to predict with certainty in a system of linked vessels in which vessel the primary ignition will occur. The maximum pressures obtainable depend on the volume ratio of the vessels and become very high when this ratio is less than 0.25, ie ignition occurs in the larger vessel.
- 2) Volume ratios are taken always to be less than 1 in the advice which follows, ie V_1 is larger than V_2 and it is assumed that primary ignition occurs in the larger of the two vessels. The volume of the pipework should be calculated and this guidance is not applicable if the pipe volume is large relative to the vessels. The pipe volume should be added to the larger vessel when calculating the ratio V_2/V_1 .
- 3) P_{max} (bar a) is the maximum explosion pressure for a given dust as measured in the standard 20 litre sphere. The pressure compression factor (CF) is estimated from the graph in **Figure 2**. Figure 2 should not be used if P_{max} exceeds 10 bar a.
- 4) The flow chart in **Figure 3** describes the relevant considerations, and depending on the system, the design pressure may be P_{max} , $P_{max} \times CF$ or $P_{max} \times (CF+1)/2$. P_{max} is expressed as bar a. If P_{max} is not known use $P_{max} = 10$ bar a.

5) The experimental trials have shown that if the pipe diameter is less than 0.1 m the probability of transmission would seem to be very low, and may be ignored for design purposes.

6) This guidance does not apply if the pipe is long enough to allow the flame front to accelerate significantly - see the I Chem E book on venting of pipelines for the current state of knowledge on this.

7) The larger vessel should not exceed 20 m³ in volume.

Two worked examples should make this clear:

a) Dust with parameters $K_{ST} = 250 \text{ bar m s}^{-1}$, $P_{max} = 8.5 \text{ bar a}$

vessels of volumes 1.5 and 4.5 m³

pipeline: diameter 0.3 m, length, 5 m, so vol = 0.35 m³

vessel ratio = 0.31

Figure 3 gives $P_{red} = CF = 2.52$

theoretical maximum pressure = $8.5 \times 2.52 = 21.4$

design systems to withstand 21.4 bar a

b) Same dust, vessels of 8 and 10 m³

pipe diameter 0.55 m, length 8 m, vol 1.9 m³

vessel ratio = 0.67

Figure 3 gives $P_{red} = CF = 1.9$

theoretical maximum pressure = $8.5 \times 1.9 = 16.2$

design pressure = $(1.9 + 1) \times 8.5/2 = 12.3 \text{ bar a}$

Venting

The progress of the explosion in a system of linked vessels is essentially the same as when the system is contained: the explosion travels through the interconnecting pipe to produce a secondary explosion. The difference is that the explosion escapes through the vent openings. The explosion pressures are thus less than when the system is contained, and the rate of pressure rise has much more importance in determining the final explosion pressure. Experiments show that the rate of pressure rise in the secondary explosion can be very high, and in practice, this needs to be taken into account in the design of effective venting.

The following guidance is based on the results of an experimental programme using various vessel volumes, pipe lengths and diameters and explosible dusts, and fully described in **reference [2]**. The guidance has been developed from the results of several hundred

explosion tests in which the total vent area in the linked system was divided so that each vessel had the same effective vent area:

$$Av_1/V_1^{2/3} = Av_2/V_2^{2/3}$$

where Av is the vent area, V the vessel volume and the subscripts refer to the vessels. Primary ignition occurs in Vessel 1 and the secondary explosion in Vessel 2.

As the vent area decreases, the relative effect of linking the vessels increases. The increase in pressure is greatest when primary ignition occurs in the larger of the linked vessels. Generally, the longer the pipe the less is the effect on the explosion pressure, but this is not always so.

The higher the explosibility of the dust, the higher the effect on the explosion pressure.

Notes for Guidance

- 1) The larger of the vessels should not exceed 20 m³.
- 2) The length of the interconnecting pipe must not exceed 15 m, and must not be less than 5 m.
- 3) The pipe area to volume of the smaller vessel in the system must not exceed 0.1.
- 4) The P_{max} of the dust should not exceed 10 bar a.
- 5) The vent area is always divided between the vessels so that the dimensionless vent area $Av/V^{2/3}$ where Av is the vent area and V the vessel volume is equal in each vessel.
- 6) The volume ratio V_1/V_2 is calculated by taking V_1 , as the larger volume and V_2 as the smaller. The volume of the connecting pipeline is ignored.

Estimating Vent Areas for Interconnected Vented Vessels

This guidance is applicable to compact vessels ($L/D < 2$), $P_{stat} < 0.1$ bar g and for vessel volumes up to 20 m³.

Figures 4 to 16 show relationships between the Maximum Reduced Explosion Pressure and the Dimensionless Vent Area for the conditions listed on each graph. The Figures can be used in two ways: to estimate the maximum reduced explosion pressure in an interconnected system when the vent area is known; and to estimate the necessary vent area to limit the maximum reduced explosion pressure to a given value.

The table shows the conditions that apply to each figure.

Figure 1	Experimental results: Maximum explosion pressures			
Figure 2	Graph of compression factor against vessel volume ratio			
Figure 3	Flow chart for design pressure selection			
Figures 4-16	Graphs giving reduced explosion pressures for different conditions			
	K_{ST} values	Volume ratio	Pipe diameter m	Location of ignition

Figure 4	=< 150	1	0.25 - 0.5	any vessel
Figure 5	=< 150	1-3	0.25 - 0.5	any vessel
Figure 6	=< 150	3-10	0.25 - 0.5	any vessel
Figure 7	=< 150	1	< 0.25	any vessel
Figure 8	=< 150	1-3	< 0.25	any vessel
Figure 9	=< 150	3-10	< 0.25	any vessel
Figure 10	=<150	1	0.25 - 0.5	any vessel
Figure 11	150-250	1-10	0.25 - 0.5	largest vessel
Figure 12	150-250	3-10	0.25 - 0.5	smallest vessel
Figure 13	150-250	1	0.15-0.25	any vessel
Figure 14	150-250	1-3	< 0.25	smallest vessel
Figure 15	150-250	1-10	< 0.15	any vessel
Figure 16	250-300	1	< 0.25	largest vessel

References

1. Lunn, G.A., Holbrow, P., Andrews, S. and Gummer, J. Dust explosions in totally enclosed interconnected vessel systems. J. Loss. Prev. Proc. Ind. 9(1), 45, (1996).
2. Holbrow, P., Andrews, S. and Lunn, G.A. Dust explosions in interconnected vented vessels. J. Loss. Prev. Proc. Ind. 9(1), 91, (1996).

Figure 1 - Experimental results: Maximum explosion pressures

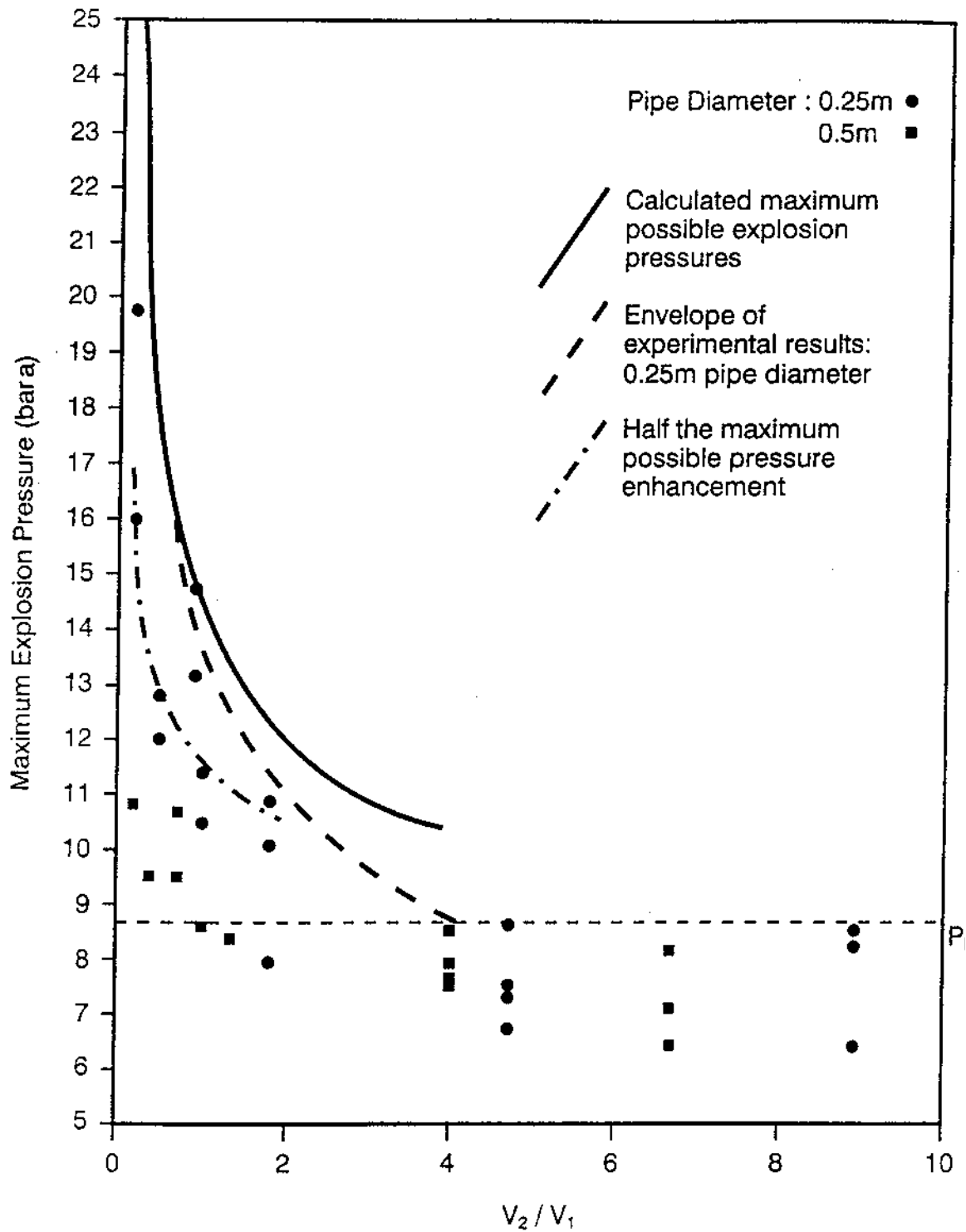


Figure 1: Maximum Explosion Pressures

Figure 2 - Graph of compression factor against vessel volume ratio

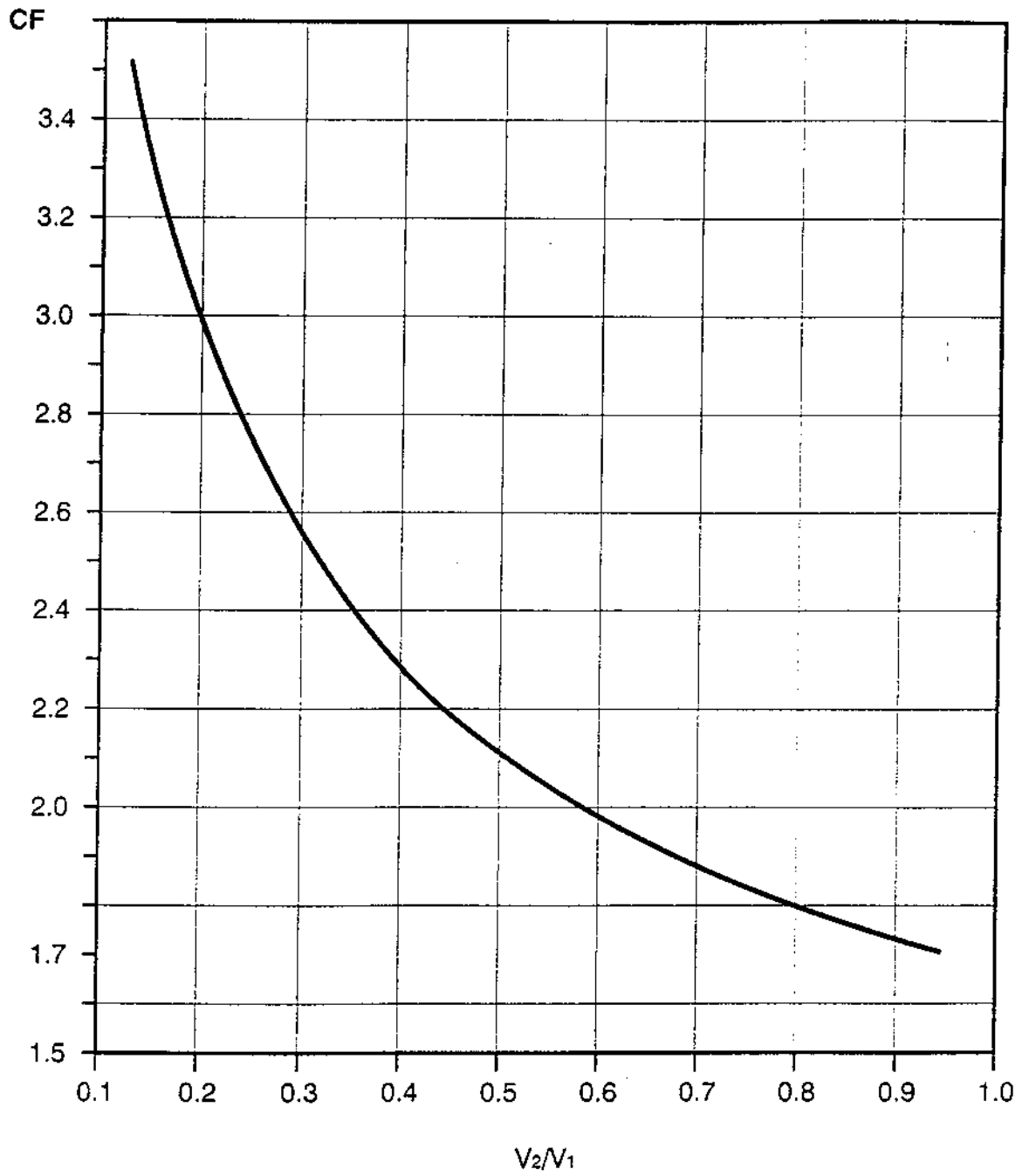


Figure 2: Compression Factor (CF)

Figure 3 - Flow chart for design pressure selection

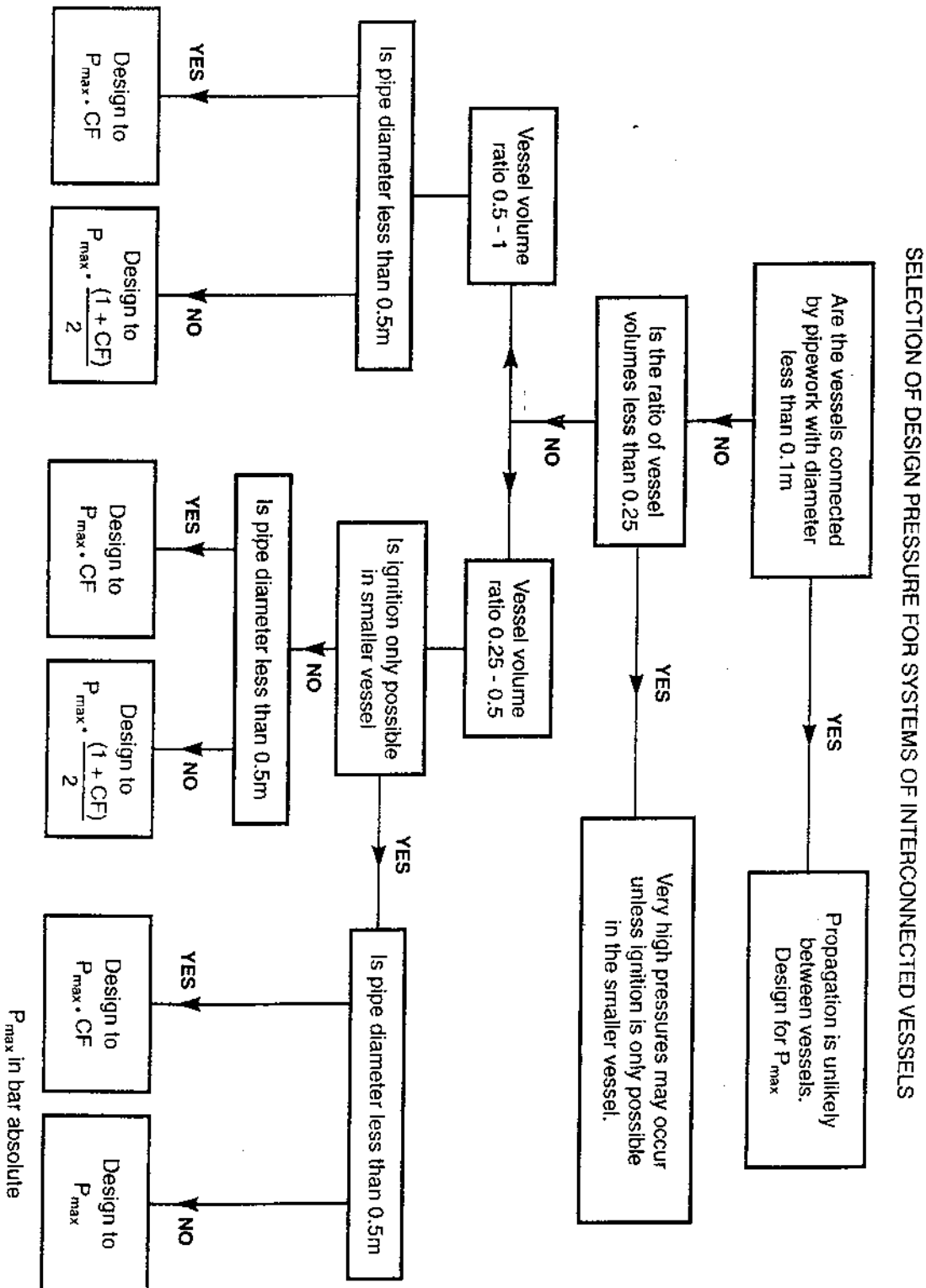


Figure 3: Flow Chart for Design Pressure Selection in Linked Contained Vessels

Figure 4 - Graph giving reduced explosion pressures for different conditions

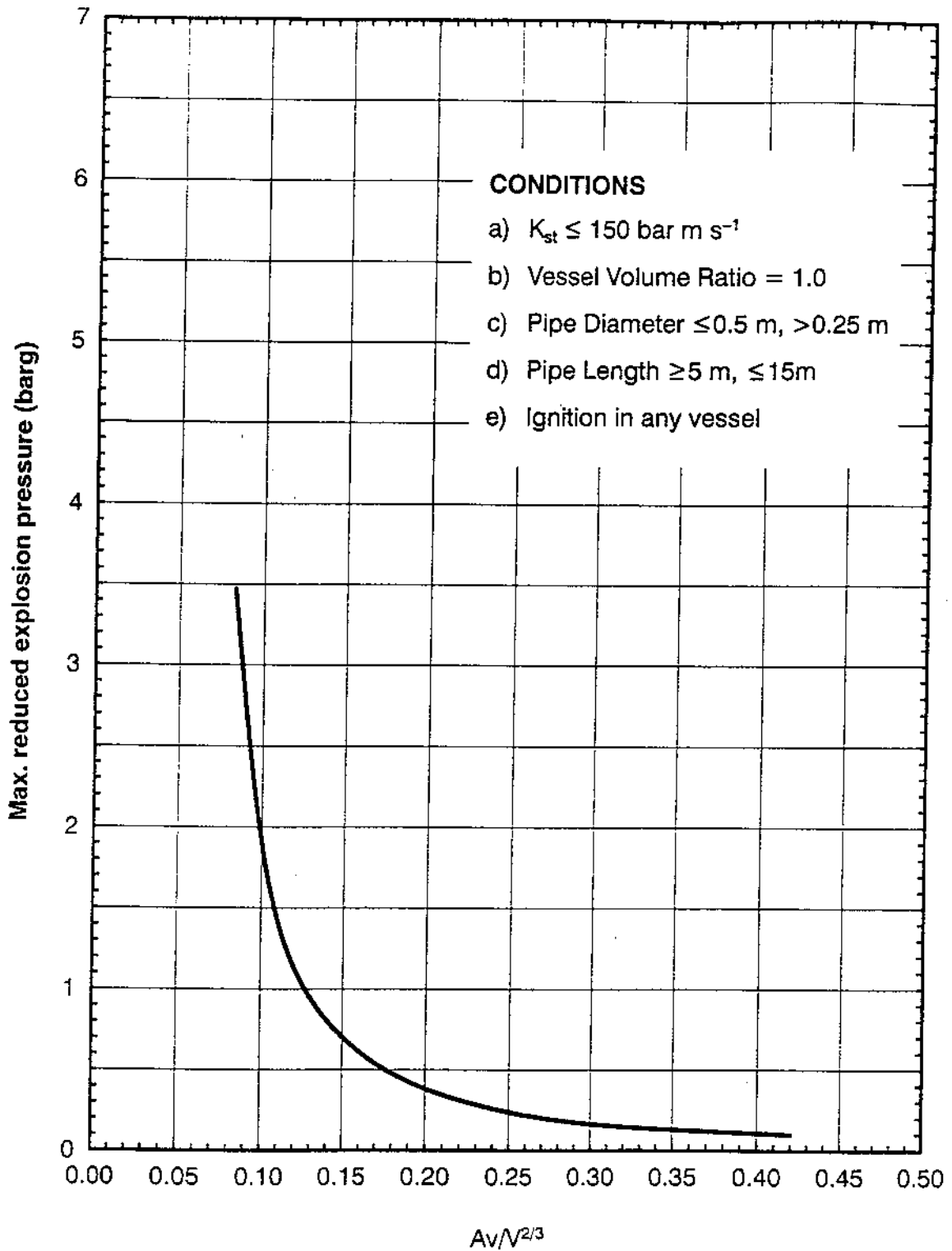


Figure 4: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 5 - Graph giving reduced explosion pressures for different conditions

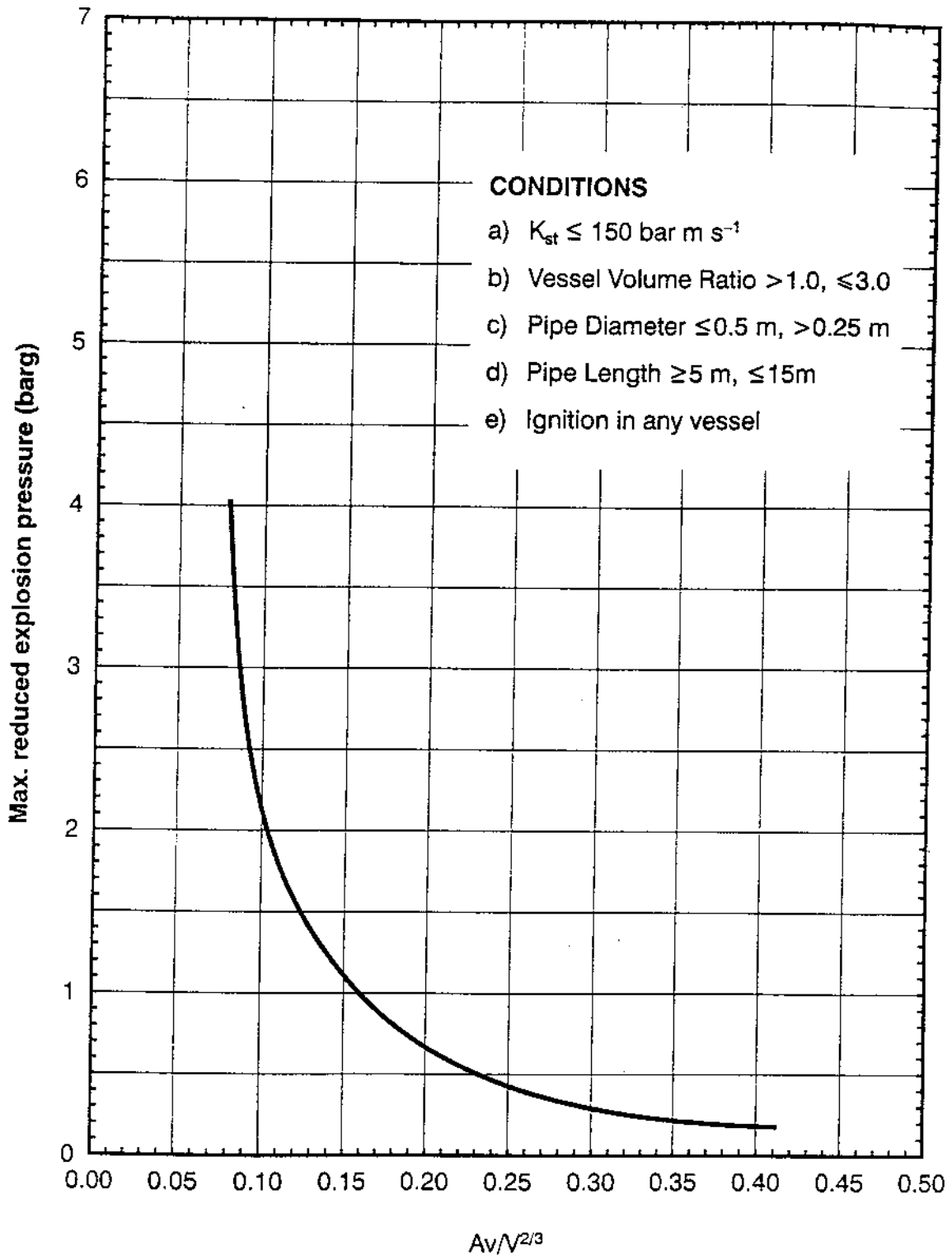


Figure 5: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 6 - Graph giving reduced explosion pressures for different conditions

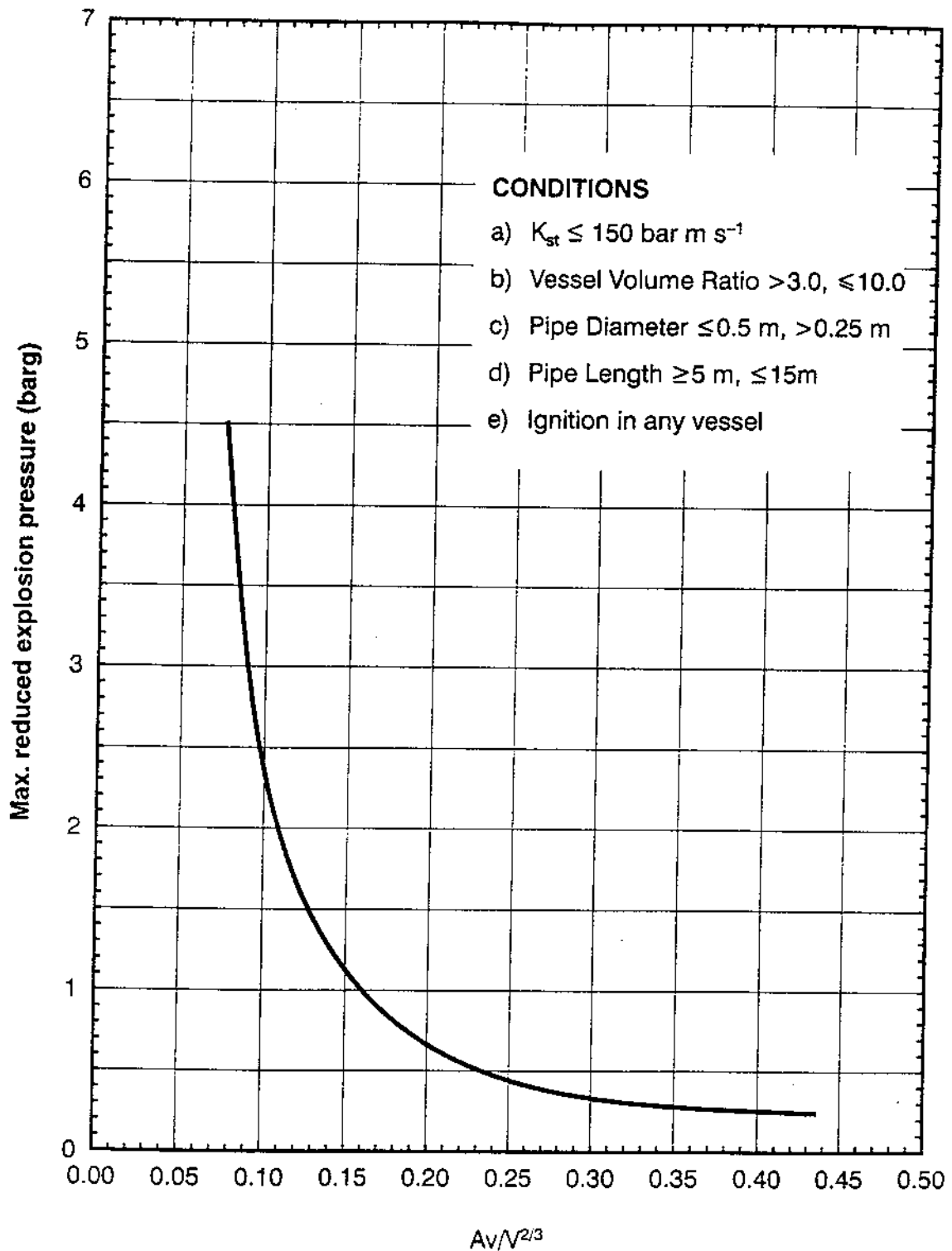


Figure 6: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 7 - Graph giving reduced explosion pressures for different conditions

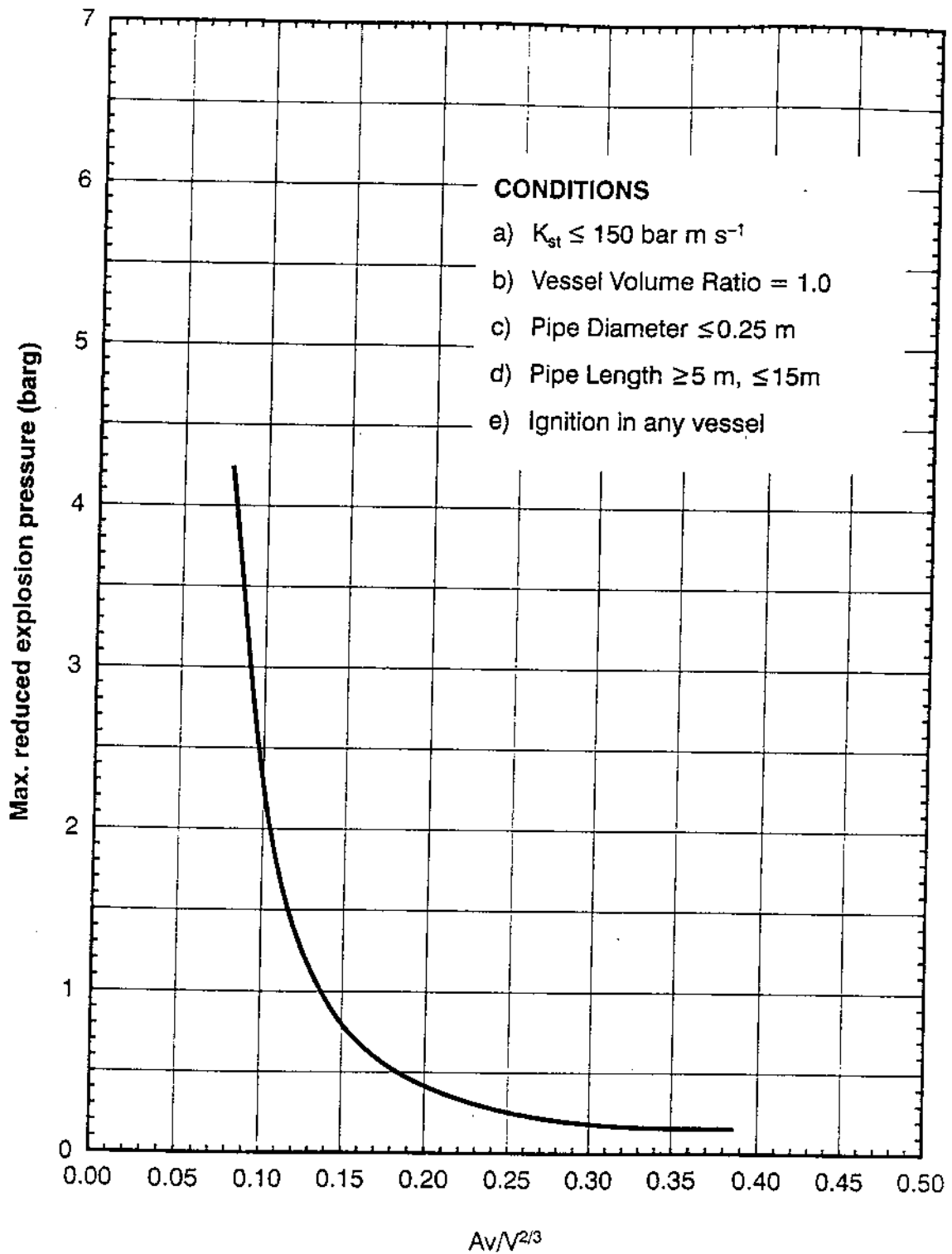


Figure 7: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 8 - Graph giving reduced explosion pressures for different conditions

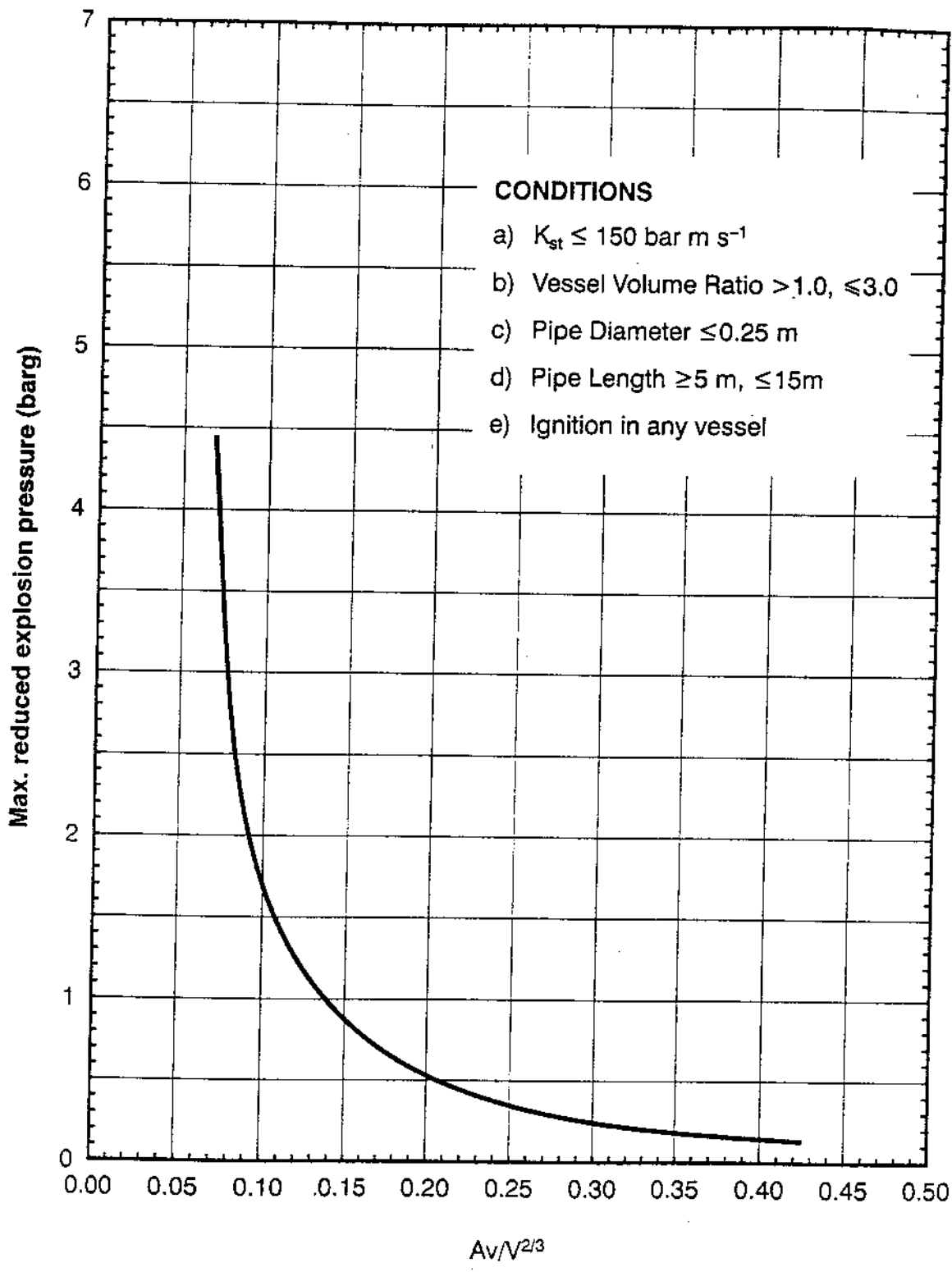


Figure 8: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 9 - Graph giving reduced explosion pressures for different conditions

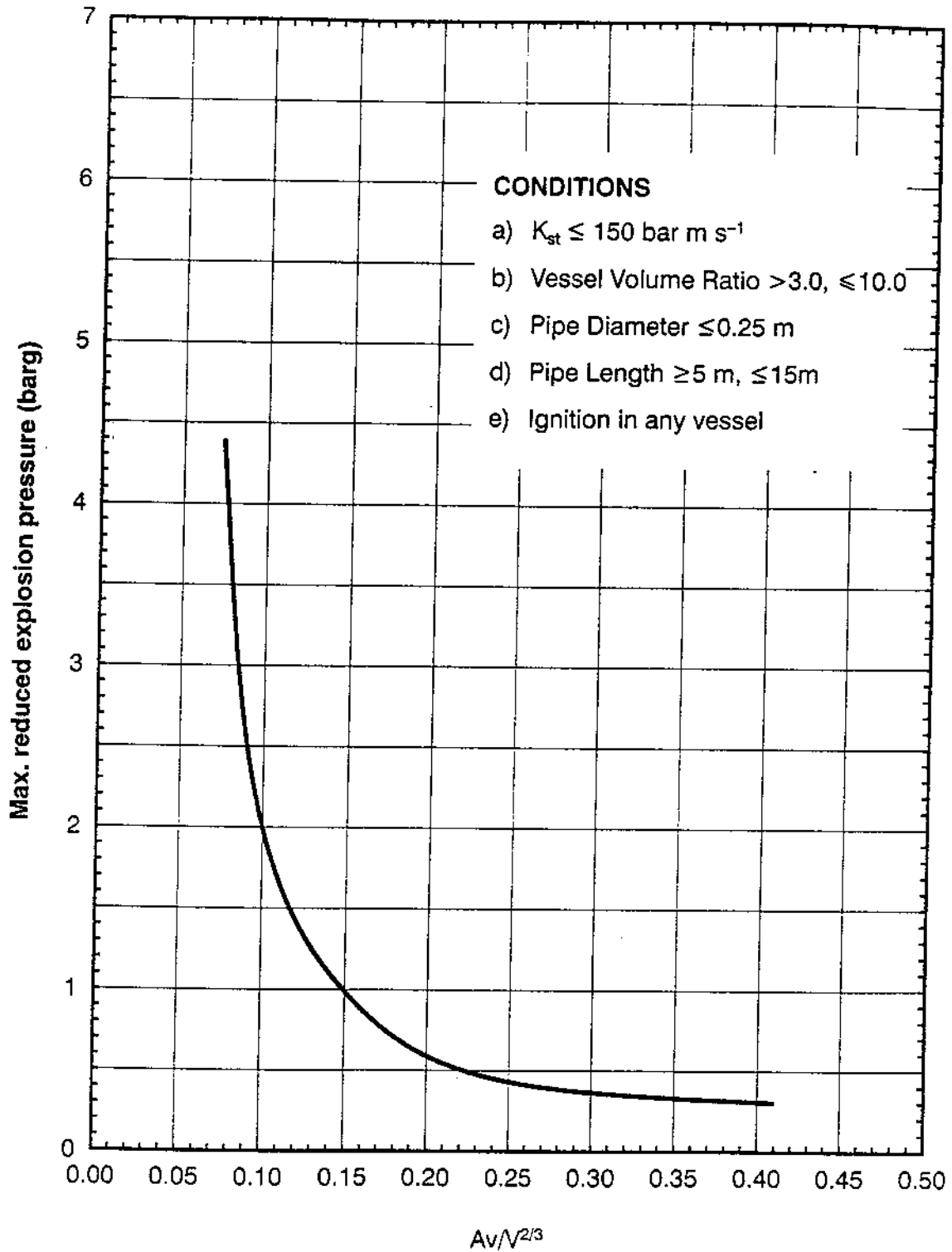


Figure 9: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 10 - Graph giving reduced explosion pressures for different conditions

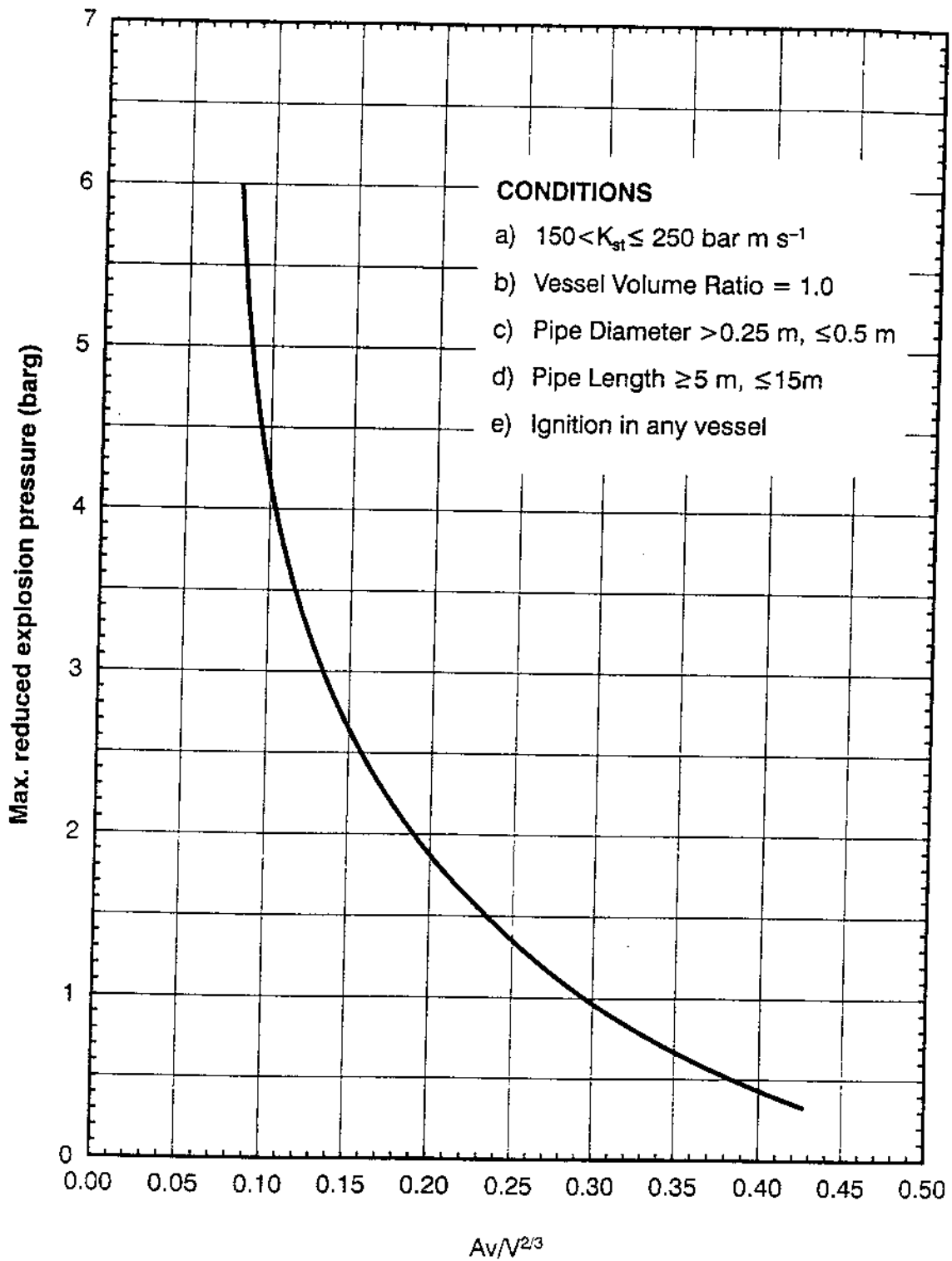


Figure 10: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 11 - Graph giving reduced explosion pressures for different conditions

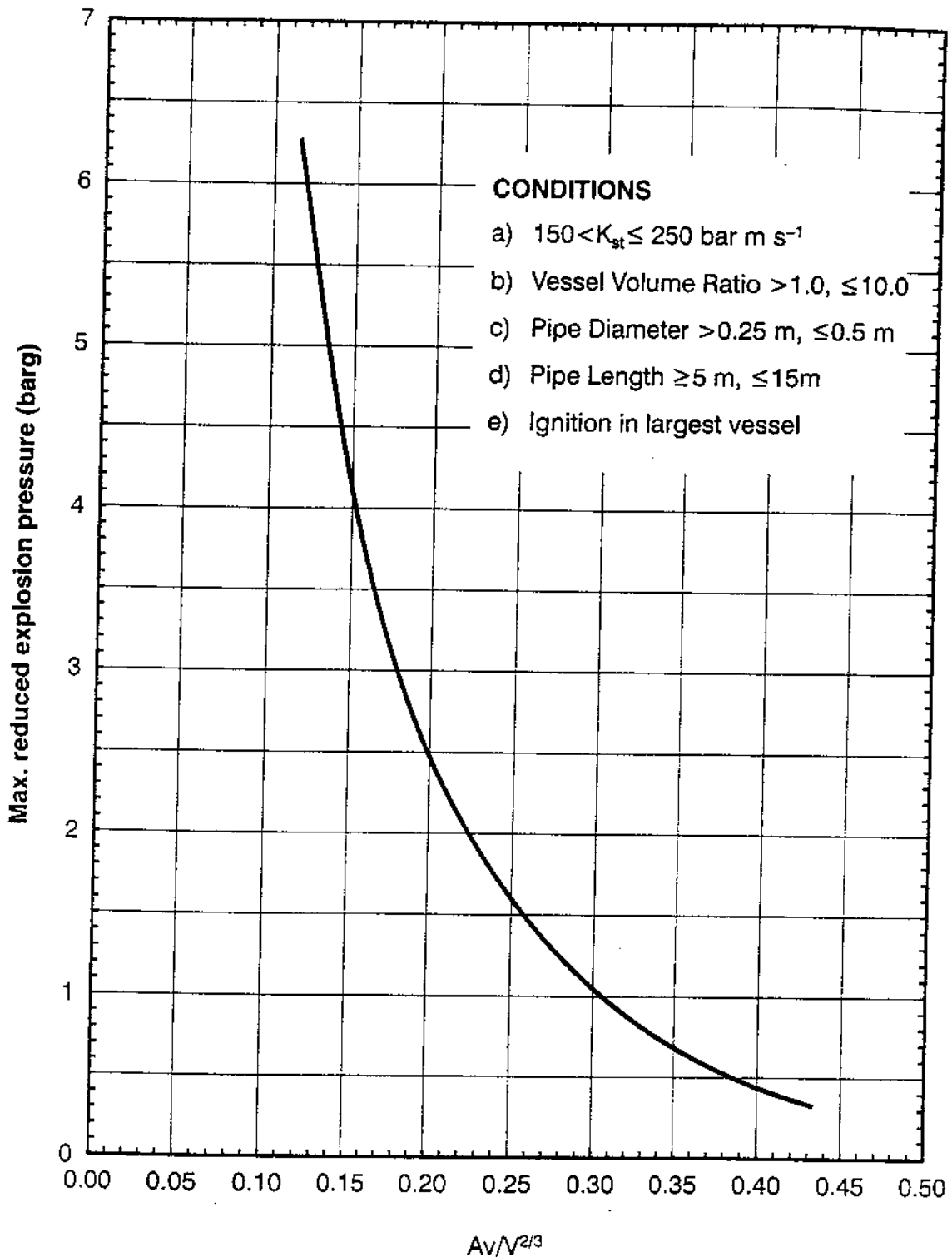


Figure 11: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 12 - Graph giving reduced explosion pressures for different conditions

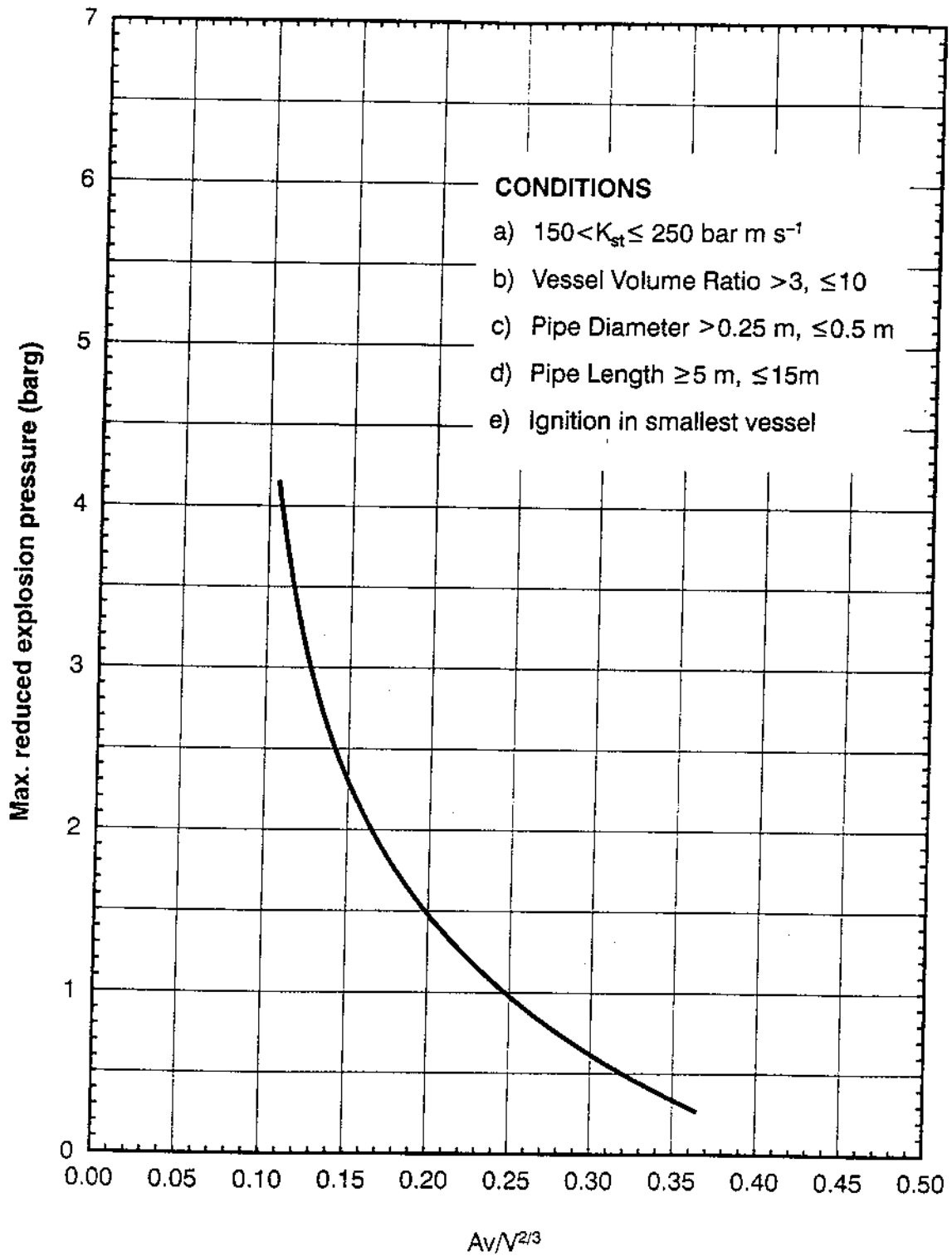


Figure 12: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 13 - Graph giving reduced explosion pressures for different conditions

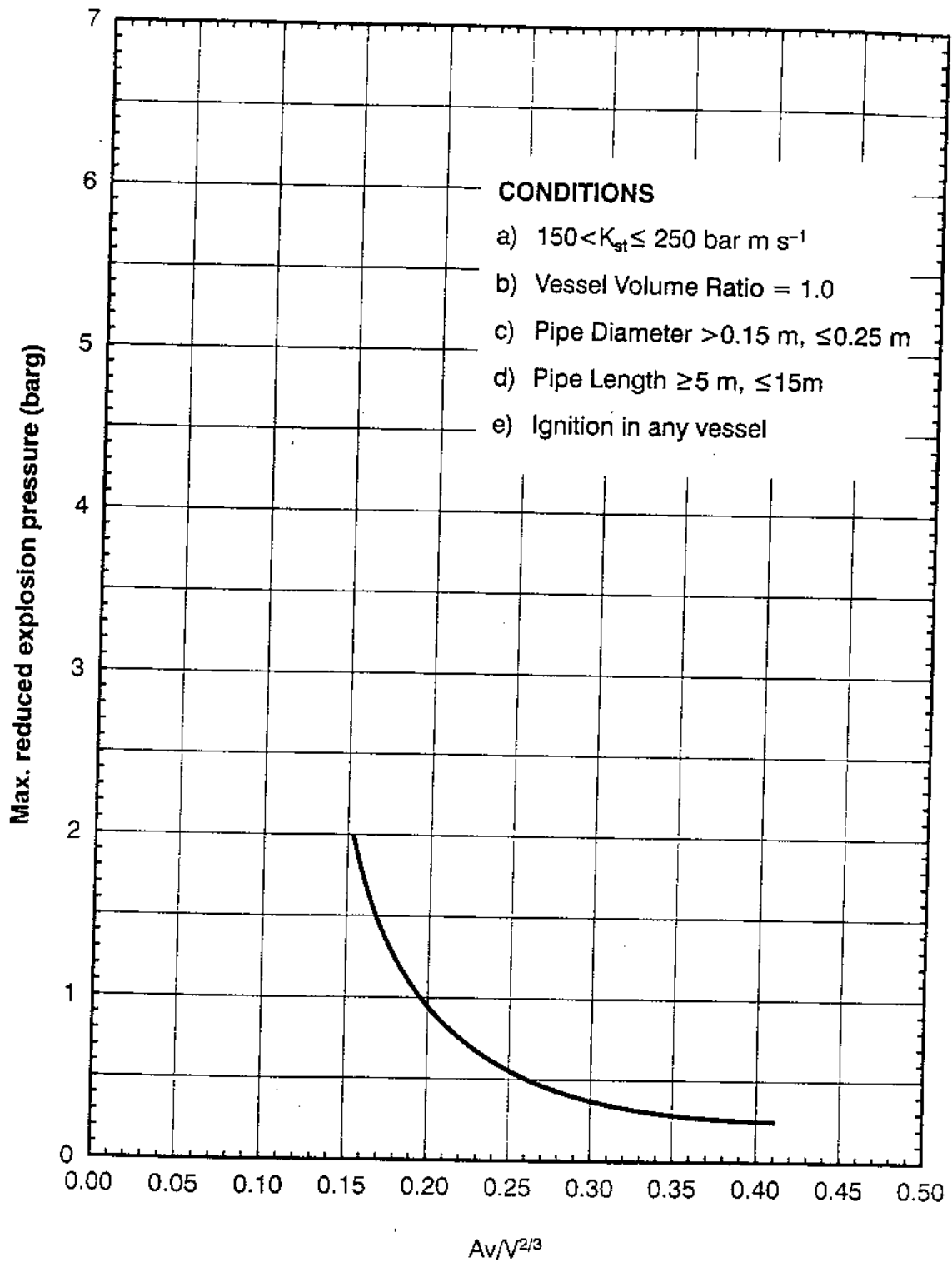


Figure 13: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 14 - Graph giving reduced explosion pressures for different conditions

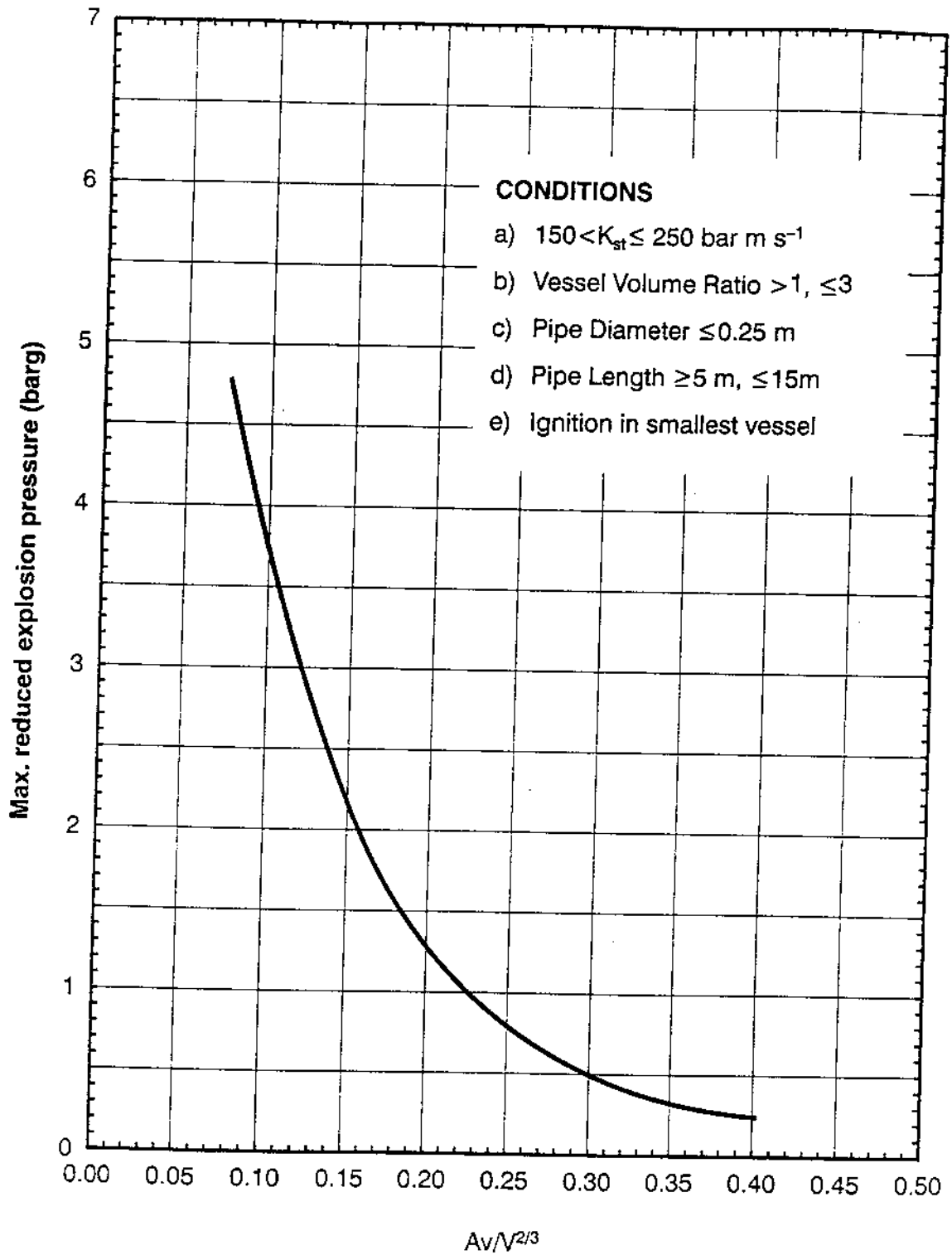


Figure 14: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 15 - Graph giving reduced explosion pressures for different conditions

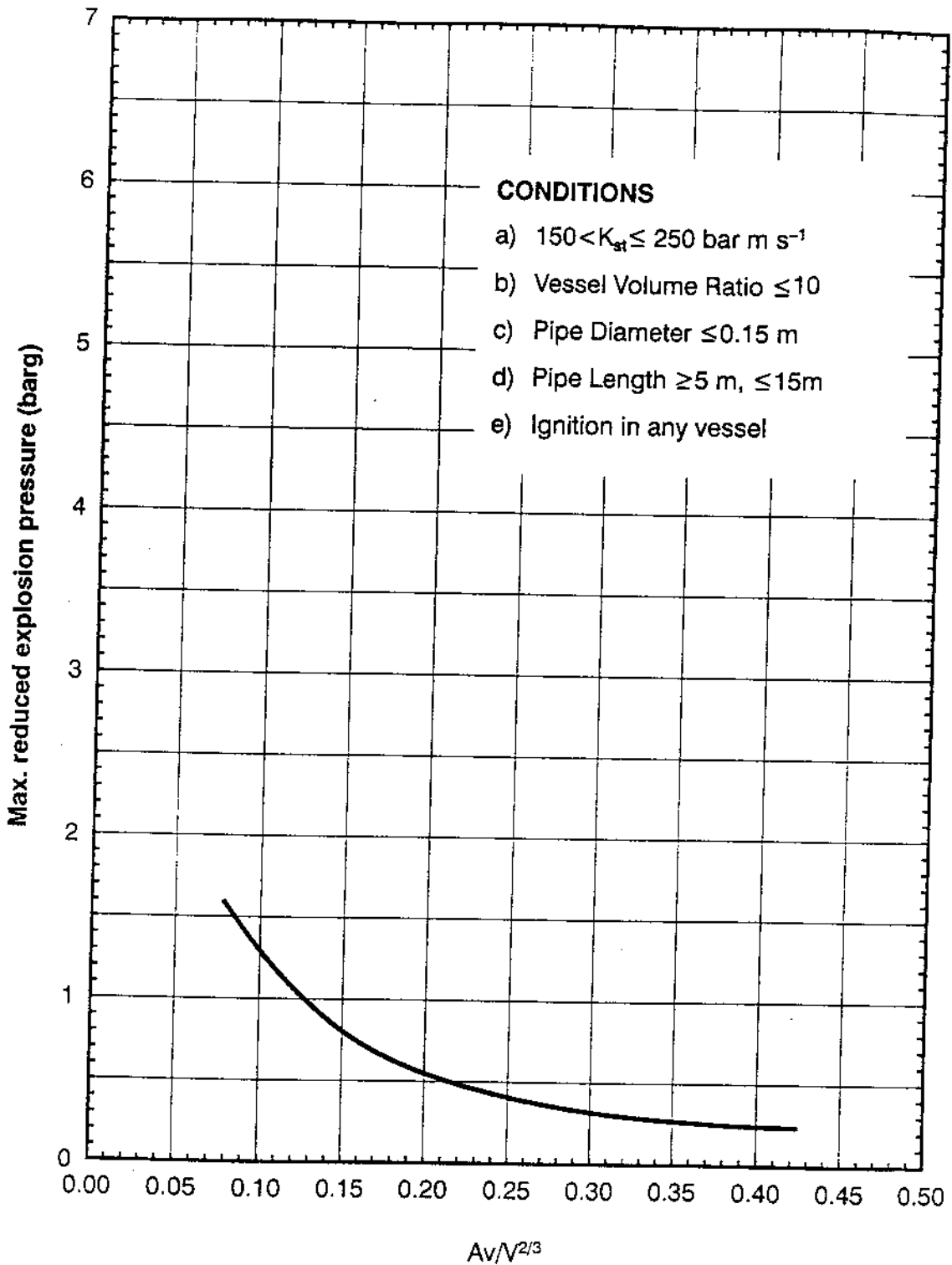


Figure 15: Max. reduced explosion pressure against $Av/V^{2/3}$

Figure 16 - Graph giving reduced explosion pressures for different conditions

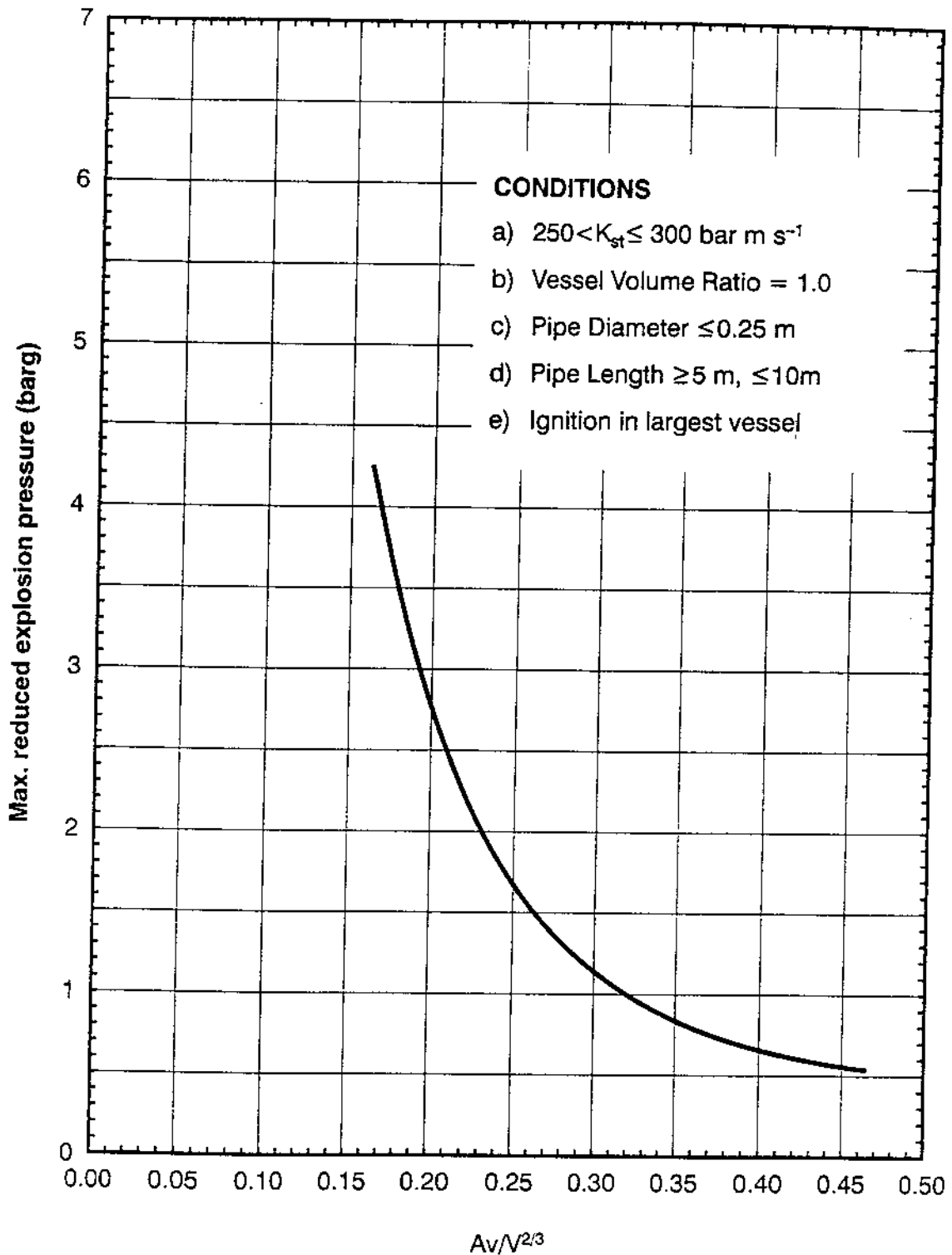


Figure 16: Max. reduced explosion pressure against $Av/V^{2/3}$