

SHRP-C-339

# **Concrete Microstructure: Recommended Revisions to Test Methods**

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## **Abstract**

This report analyzes and evaluates the results of research performed by SHRP for possible modifications to existing standard methods and specifications from the American Society of Testing and Materials (ASTM), the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials (AASHTO), and the Pennsylvania Department of Transportation. The evaluation criteria are described. Both specific and general recommendations are made. Implications of results of packing for aggregate grading on ASTM C33 are discussed. An extensive appendix contains trilinear packing diagrams.



## Executive Summary

Specifications, test methods, and standard practices for concrete have been reviewed, evaluated, and revised in light of other work completed under SHRP's Concrete Microstructure project C-201. The recommended revisions to American Society for Testing and Materials (ASTM) and American Concrete Institute (ACI) specifications have been presented with corresponding reasons for changing them. These recommendations take two forms: specific revisions to existing standards and specifications, and general recommendations regarding existing standards and specifications. Most of the changes are related to the packing model and the curing/hydration models.

Standards and specifications whose content is associated with the various research tasks of project C-201 were thoroughly reviewed in light of any new information generated by the research in those tasks. When new information indicated that an existing standard should be altered, these revisions were presented in a form that could be adopted by the governing technical committees of ASTM or ACI. The technical evidence for the suggested revisions is either indicated directly within the text of this section, or else a reference is provided to other SHRP reports.

Extensive discussion is given to ASTM C33 ("Standard Specification for Concrete Aggregates") and the potential for better concrete mixture designs from revised concrete coarse aggregate size number designation grading requirements. Also discussed is the impact of the packing model on other aggregate grading-oriented specifications, such as ASTM C330 ("Standard Specification for Aggregates for Lightweight Structural Concrete") and ASTM D448 ("Standard Classification for Sizes of Aggregate for Road and Bridge Construction"). Each of these specifications may be improved based on knowledge gained from the packing model.

The curing/hydration model work leads to both direct suggested revisions to test methods and to discussion of future applicability of curing models in concrete practice, especially those practices outlined under the auspices of ACI. Included among these are the standard practices presented in ACI 308 ("Standard Practice for Curing Concrete"), ACI 306 ("Cold Weather Concreting"), and ACI 305 ("Hot Weather Concreting"). The specific revisions based on the curing/hydration work center primarily on ASTM C1074 ("Standard Practice for Estimated Concrete Strength by the Maturity Method") and ASTM C1064 ("Standard Test Method for Temperature and Freshly Mixed Portland-Cement Concrete"). In these specifications, some existing wording is found to be incorrect, while other sections giving

data values are extended beyond their present state. Additional constraints on procedures described in both specifications are also suggested.

The investigations of concrete microscopy result in comments made herein regarding ASTM C856 ("Standard Practice for Petrographic Examination of Hardened Concrete"). Two alternative methods of fluorescent light microscopy (transmitted and reflected modes) are described in a supplemental report dealing with concrete microscopy. These two methods are discussed here, within the scope of this work, in relation to their merit for inclusion in ASTM C856. It appears that transmitted light fluorescence microscopy may be a useful tool, but presently the accuracy, precision, and bias of the method are not clearly understood. Moreover, the results obtained from the technique are very operator-dependent. Reflected light fluorescence microscopy also seems promising as a tool in standard practice; however, more data and experience with the method must be gained before it is included in ASTM C856.

Summary tables and figures regarding the revised specifications are also provided where possible. All suggested revisions are directed toward concrete practitioners in general, but are more specifically written for review by the technical committees of ASTM, ACI, and AASHTO.

## Introduction

The objective of this work was to analyze, evaluate, and integrate into standard practices, methods, and specifications, where appropriate, the results of the research done under SHRP's Concrete Microstructure project C-201. This work also sought to develop recommendations for new standards or specifications to bridge gaps in existing knowledge. The work has been evaluated primarily in relation to the standards and specifications of the American Society of Testing and Materials (ASTM), the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials (AASHTO), and the Pennsylvania Department of Transportation (PADOT). These organizations are representative of the regulatory or advisory groups associated with concrete construction and practice.

Throughout the contract, this phase has interacted with the research objectives to develop a set of research results which could be most easily integrated into existing standards. Several existing standards and specifications that might be affected by the work of the first three tasks are presented in Table 1. To aid in the evaluation of the contract's research topics, a set of matrices relating these research topic areas to specific test methods or recommended practices was constructed for ASTM, ACI, AASHTO, and PADOT. As the research progressed, these matrices have been updated and distributed. The final version of these matrices is presented.

To achieve the objectives of this report in a logical, precise way, a set of criteria for evaluation of the research tasks was developed. In addition, discussion was held with governmental employees in the concrete construction area, contractors, and construction crews during field testing and verification for more insight toward the integration of this work into existing standards and specifications.

**Table 1. Candidate test methods, standard specifications, and recommended practices for evaluation.**

Type	Description or Title	<u>Method or Spec. No.</u>			Typical State DOT (PA)
		ASTM	ACI	AASHTO	
Test Method	Slump of fresh concrete	C143		T-119	PTM 600
" "	Flexural strength of concrete	C78		T-97	PTM 603
" "	Compressive strength	C39		T-22	PTM 604
" "	Unit weight yield air content of fresh cement	C138		T-121	PTM 613
" "	Air content of fresh concrete	C231		T-152	PTM 615
" "	Time of set	C403		T-179	PTM 632
" "	Compressive strength of mortar	C109		T-106	
" "	Autoclave expansion of cement	C151		T-107	
" "	Normal consistency of cement	C187		T-129	
" "	Fineness of portland cement	C430		1-192	
" "	Bleeding of concrete	C232		T-158	
" "	Splitting tensile strength	C496		T-198	
" "	Chloride permeability			T-277	
" "	Making/curing field test specimens	C31		T-23	
" "	Temperature of fresh concrete	C1064			
" "	Penetration resistance	C803			
" "	Pullout strength	C900			
" "	Rebound number	C805			
" "	Making/curing lab test specimens	C192		T-126	
" "	Project concrete strengths	C918			
" "	Accelerated curing/testing	C684			
Std. Spec.	Physical and chemical requirements for portland cement	C150		M-85	SECT. 701
" "	Physical and chemical requirements for blended cement	C395		M-240	SECT. 701
" "	Ready mixed concrete	C94		M-157	SECT. 704.1
" "	Volumetric batching and continuous mixing	C685		M-241	
" "	Aggregate for concrete	C33			
" "	Aggregate for road/bridge construction	D448			
" "	Concrete admixtures (except AEA)	C494	212.1	M-241	SECT.711.3
" "	Pozzolanic materials	C618			SECT.724.2
" "	Ground blast furnace slag	C989			
Rec. Pract.	Petrographic examination	C856			
" "	Maturity Method for concrete	C1074			
" "	Air-void analysis	C457			
" "	Durable concrete		201.2		
" "	Selecting proportions for normal weight concrete		211.1		
" "	Using admixtures		212.2		
" "	Measuring, mixing, transporting and placing concrete		304		
" "	Hot weather concreting		305		
" "	Cold weather concreting		306		
" "	Curing concrete		308		
" "	Consolidation of concrete		309		
" "	Construction of concrete pavements/bases		316		
" "	Construction of bridge decks		345		

## Criteria for Evaluation and Integration

As discussed in the main report Concrete Microstructure<sup>1</sup>, Section V, criteria have been established that allow for detailed, analytic review and evaluation of the research that pertains to integration of this work into existing standards and specifications, as well toward recommendations of new standards and specifications. These criteria, discussed below, can be broken down into two groups: those dealing with exact experimental procedure requirements; and those dealing with significance and implementability of research findings.

The primary criterion for evaluating a test method or specification involves the experimental precision and bias of a model's output or the results of experimentation. A second criterion involves the relative significance of the research findings. While no definitive explanation of "significance" in this context is available, the estimation of significance is based on the research team's myriad experiences with concrete applications. Thus, a research finding which affects a standard or specification which in turn affects many other specifications (e.g., ASTM C33 - "Standard Specification for Concrete Aggregates"), or is deemed critical to at least one important aspect of concrete use and specification (e.g., ACI 211.1 - "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete"), would garner a rating of "high significance."

Similarly, findings considered of lesser use or applicability would be rated "low significance" or "medium significance." Although these ratings are somewhat qualitative, they do allow for a more rigorous analysis and evaluation of the findings than would be possible in their absence.

Finally, the implementation of the research findings to specifications and standard practices is evaluated. Certain findings, such as the work performed on activation energy determination, may very easily be transferred to existing standards (in this case, ASTM C1074 "Standard Practice for Estimated Concrete Strength by the Maturity Method"). Such work would be deemed "easily implemented." Other findings, although possibly significant in depth and applicability, may for some reason not be readily integrated in standard specifications and practices. These findings might be termed "difficult to implement."

How a research topic or finding fares with respect to these established criteria determines how recommendations to existing standards and specifications related to that topic are presented later in this report.

## Status and Format for Recommendations

The final status of the evaluation and revision of standard specifications is best demonstrated through the matrices in Fig. 1 and Fig. 2 for ASTM and ACI standards, respectively. These figures indicate which standards have been evaluated or affected by the work in project C-201. A detailed discussion of the evaluation and impact are presented later in this report, but it is obvious that in general, the number of standards

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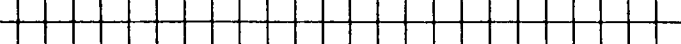
<sup>1</sup>Roy, D.M. 1993. Concrete Microstructure. *Strategic Highway Research Program*. SHRP-C-340.

## ASTM

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KEY: S = specific recommended revision  
G = general recommendation

**Figure 1. Matrix of ASTM Standards and Specifications reviewed.**

[illegible]

**Figure 2. Matrix of ACI Specifications and Practice reviewed.**

affected by this research is only a fraction of those initially listed for evaluation (see Table 1, p. 6). Only ASTM and ACI are represented here as their standards are directly influenced by the research. The PADOT and AASHTO specifications are, in most instances, congruous with the ASTM and ACI specifications.

The results are presented in two major sections, and the content of each of these sections is included in Fig. 1 and Fig. 2. The first section is made up of a detailed evaluation of the specific recommended revisions to standards. The second section evaluates standards that might be improved as a result of knowledge gained from the research of this contract. These more general recommendations are still limited because the knowledge has not yet matured to indicate the need for a specific revision.

No specific new standard specifications, test methods, or recommended practices are suggested at this time.

However, this report presents a test method for permeability that may be of future interest.

## **Recommended Specific Revisions**

Several recommended specific revisions to existing ASTM and ACI standard specifications are described in this report. They are in a format designed to present the existing wording or intent of a specification, the reason(s) for revising it, and a suggested revised wording to the specification. Any new or revised wording is shown in boldtype, while unchanged wording is shown in normal typeface. Note that the heading of each specification discussion, including the number designation and title of the specification, are also shown in boldtype for clarity.

### ***ASTM C94:***

#### ***Standard Specification for Ready-Mixed Concrete***

Work related to the packing model has shown that it is possible to obtain different aggregate gradings (per ASTM C33) which have the same nominal maximum size. For example, ASTM C33 size numbers 5, 56, and 57 all are identified by the same nominal maximum size, namely 1 in. (25.0 mm), but each has a different grading. Inclusion of the size number designation on the batch ticket (which is only furnished when the purchaser requests it - per section 14.2 of this standard) would help in allowing for more appropriate remedial response if segregation or bleeding is observed during the field application of the mix.

The packing report, which is a separate written statement under SHRP C201, discusses the effect of various grading differences on the placing and workability characteristics of fresh concrete. Due to the findings detailed in that report, inclusion of this additional batch ticket information is deemed necessary. Such information could aid the purchaser if remedial action during placement of consolidation is needed. In sum, this recommendation results in necessary tighter control and observation of the delivered product.



It is recommended that a new section be added to the specification, and that appropriate renumbering of subsequent sections be done. Specifically, existing sections 16.2.7 and 16.2.8 should be renumbered to **16.2.8** and **16.2.9** respectively, and the new section 16.2.7 should read

**16.2.7 Size number designation per ASTM C33,**

*ASTM C685:*

*Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing*

For the same reasons discussed in the previous recommended revision, additional batch ticket information is recommended for this specification also. Namely, sections 14.2.6, 14.2.7, and 14.2.8 should be renumbered to **14.2.7**, **14.2.8**, and **14.2.9** respectively, while the new section 14.2.6 shall read

**14.2.6 Size number designation per ASTM C33,**

*ASTM C1074:*

*Standard Practice for Estimated Concrete Strength by the Maturity Method*

Many temperature versus time profiles have been recorded in association with the curing and hydration model work<sup>2</sup>. The data show that changes in temperature are significant over the first 10 to 16 hours for all cements tested, but these changes with respect to time are drastically reduced after 20 hours. This finding suggests that the recommended time intervals for data collection in ASTM C1074 be relaxed to represent this determination (See Fig. 3). Specifically, it is suggested that the existing wording of the specification

- 7.1 . . . the recording time interval shall be 1/2 h or less for the first 48 h and 1 h or less thereafter.

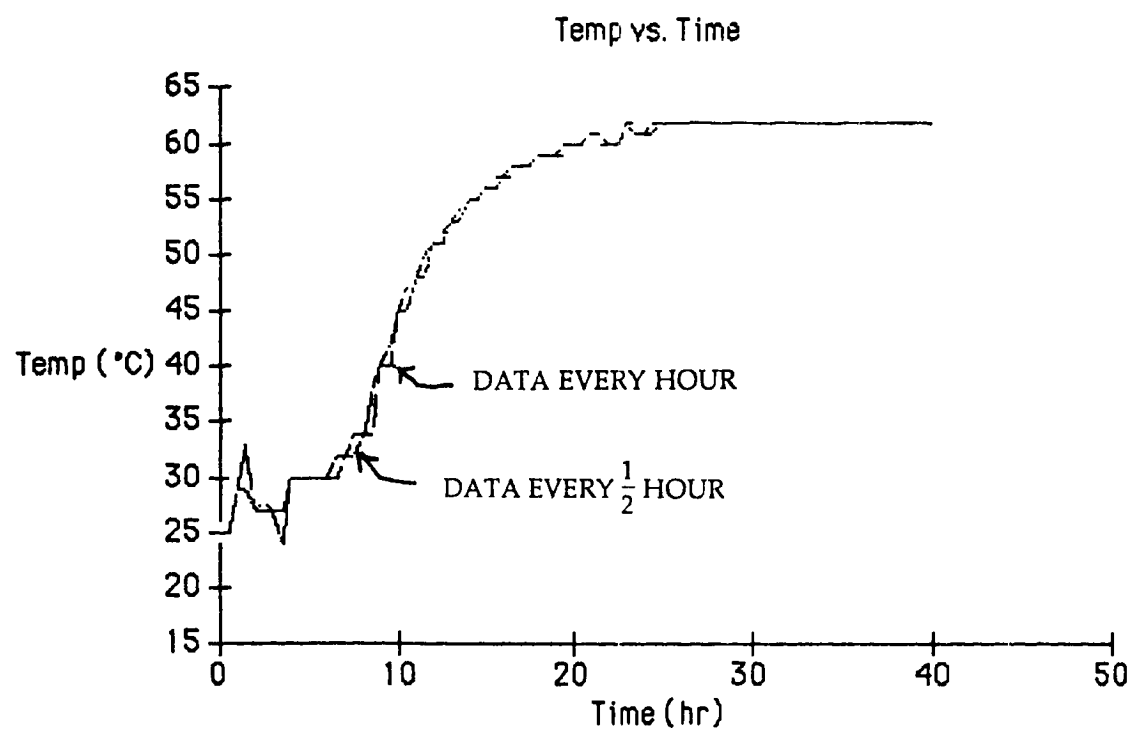
be changed to

- 7.1 . . . the recording time interval shall be 1/2 h or less for the first **24** h and 1 h or less thereafter.

A second revision is in the form of note to be added to section 8.2. The content of the note is straightforward, but it is necessary in view of the foreseeable increased use of maturity functions to predict concrete properties in the future. Specifically, the following note is suggested as an addition under section 8.2, with all subsequent notes renumbered accordingly:

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<sup>2</sup>Roy, D.M. 1993. Maturity Model and Curing Technology, *Strategic Highway Research Program*. SHRP-C-625.



**Figure 3. Typical adiabatic temperature evolution.**

**8.2 NOTE 2 - The number of specimens used is a function of the criticality and desired precision of the results.**

Additionally, it has been found that the activation energy for the Type I cement used in the field-testing portion of SHRP's curing model was significantly higher than the value currently recommended in the appendix for maturity functions (App. X1 - Nonmandatory Information). We suggest a broadening of the listed approximate values to include this new data, and also a change of the approximate value of  $Q$ , the activation energy divided by the gas constant, from a single value to a more appropriate range of values. Specifically, the recommended revision includes a change from

X1.3.1 . . . values in the range of 40,000 to 45,000 . . .

X1.3.1 Thus, an approximate value of  $Q$ , the activation energy divided by the gas constant, for use in Eq. 2, is 5000°K.

to

X1.3.1 . . values in the range of 40,000 to **48,000** . . .

X1.3.1 Thus, **approximate values** of  $Q$ , the activation energy divided by the gas constant, for use in Eq. 2, **range from 4800°K to 5700°K**.

It appears that the statement made from ASTM standards in section A1.1.8, which reads (in part) "determine the slope and intercept of the best fitting straight line through the data. . . ," is incorrect<sup>3</sup>. Furthermore, use of this technique may lead to misleading results if insufficient data are available. Therefore, it is recommended that this section be further investigated by the technical committee in charge of this specification.

Finally, additional relevant data is furnished for informational purposes in a recommended new entry in the appendix, namely

**X1.3.1.1 Blended cements are expected to have different activation energies from those of pure cements. For example, slag cements and fly ash cements have shown higher activation energies on an equal mass basis.**

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<sup>3</sup>See note 2, p.6.

### *ASTM C1064:*

#### *Standard Test Method for Temperature of Freshly Mixed Portland-Cement Concrete*

In field practice, concrete is not placed in equidimensional containers in order to measure its temperature. Usual practice is to place a shovelful in a wheelbarrow and cover it with burlap, with the wheelbarrow being the acceptable "container" specified in section 4.1 of this Standard Test Method. With the anticipated increased use of maturity methods for analysis and design of concrete performance parameters, a difference of as little as one degree may influence a strength-gain or heat-generation simulation.

Since most computer simulations assume a starting temperature in the center of a symmetrical sample, it is logical to attempt to mimic this assumption in the laboratory or field as well as possible. Use of the CIMS program<sup>4</sup> on the curing/hydration models has shown that the geometry of samples greatly affects temperature and heat gain/loss, and even though this recommendation is minor in scope, it is appropriate based on the considerable amount of time which may pass between sample collection and temperature reading (sections 7.2 and 7.3). The specific recommended addition to this specification is shown below.

- 7.1 . . . submerged a minimum of 3 in. (75 mm). **If the specimen is large enough such that greater than 3 in. (75 mm) of concrete may cover the temperature measuring device in any direction, the temperature measuring device shall be submerged to the approximate geometric center of the concrete sample.** Gently press the concrete . . .

Additionally, it is recommended that ASTM Subcommittee C09.03.03, having technical charge of this Standard Test Method, investigate the specification of a standard 12-inch long concrete cylinder mold, 6" in diameter and filled half-full, as a possible improvement to this Standard Test Method. Specification for an appropriate temperature-measuring device to be used with this container should also be included in the specifications.

### *ASTM C33:*

#### *Standard Specification for Concrete Aggregates*

Particle packing and its effects on properties have been effectively modeled throughout the course this research. Each of the modeled behaviors has been observed during laboratory observation, and the densities for dry packing generated by the model have been verified by experimentation<sup>5</sup>.

The packing model affects ASTM C33 in several ways. First, it allows for a critical evaluation of the existing size number designation grading requirements. Second, it

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<sup>4</sup>See note 2

<sup>5</sup>Roy, D.M. 1993. Concrete Components Packing Handbook. *Strategic Highway Research Program*. SHRP-C-624.

facilitates analysis of the effects of those gradings on subsequent dependent specifications, such as ACI 211.1.

Existing ASTM C33 grading requirements (Table 2) may be improved by revision of that specification, which identifies the grading requirement for each size number. Revision is recommended because use of the packing model has demonstrated that concretes made from components proportioned by varying currently allowable gradings within the standard will have widely varying packing densities. Moreover, the potential exists for poorer packing, and even for a packing diagram that is less tolerant to error in the proportioning of fine and coarse aggregates during the batching process.

The analysis of Table 2 of ASTM C33 was carried out in the following manner: For each size number designation, five combinations of the currently allowable size fractions were developed. One combination emphasized the largest allowable particle sizes for a size number. In other words, for the specified allowable ranges in Table 2 of ASTM C33, the highest allowable percentage of large aggregate particles was used, while the minimum amounts of the medium- and small-sized fractions were used (H). The second combination emphasized the aggregate in the middle of the size ranges for a specified size number, thus minimizing the percentages of the smallest and largest particles in the size number (M), while a third combination consisted of the highest percentage allowable of the smallest particle in a size number designation, with a minimum of medium- or large-sized particles (L).

The fourth combination resulted from using aggregates from the largest and smallest size fractions, but minimizing the percentage from the medium sizes (HL). The final combination was developed using the mean value of the existing allowable percentages in each of the size fraction designations (ASIS). A summary of the percentage combinations used, and their associated "short-hand" nomenclature, is given in Table 3.

These five combinations were input into the packing model. The density distribution for a three-component system was determined for each combination within a size number designation. The other two components were Type I cement and fine aggregate, where the cement size distribution was in accordance with that suggested by Mehta<sup>6</sup> and the fine aggregate size distribution was determined using mean values of the allowable percentages passing in Section 5.1 of C33. Since it has been determined that the packing of such a three-component system is only a very weak function of the finest particles (the cement), the recommendations that follow are likely appropriate for other cement types with gradings similar to Type I.

The packing densities were then generated on trilinear packing diagrams and analyzed, resulting in the following discussion of recommended revisions.

It is a general conclusion that there are certain of the combinations described above for each size number designation which result in poor packing density characteristics, and

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<sup>6</sup>Mehta, P.K. 1986. Concrete: structure, properties, and materials. Prentice-Hall. Englewood Cliffs, NJ.

**Table 2. Grading requirements for coarse aggregates. Source: ASTM C33.**

Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Weight Percent												
		4 in. (100 mm)	3½ in. (90 mm)	3 in. (75 mm)	2½ in. (63 mm)	2 in. (50 mm)	1½ in. (37.5 mm)	1 in. (25.0 mm)	¾ in. (19.0 mm)	½ in. (12.5 mm)	¾ in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)
1	3½ to 1½ in. (90 to 37.5 mm)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...
2	2½ to 1½ in. (63 to 37.5 mm)	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...
3	2 to 1 in. (50 to 25.0 mm)	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...
157	2 in. to No. 4 (50 to 4.75 mm)	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...
4	1½ to ¾ in. (37.5 to 19.0 mm)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...
157	1½ in. to No. 4 (37.5 to 4.75 mm)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...
5	1 to ½ in. (25.0 to 12.5 mm)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...
56	1 to ¾ in. (25.0 to 9.5 mm)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...
57	1 in. to No. 4 (25.0 to 4.75 mm)	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...
6	¾ to ¾ in. (19.0 to 9.5 mm)	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...
57	¾ in. to No. 4 (19.0 to 4.75 mm)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...
7	½ in. to No. 4 (12.5 to 4.75 mm)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...
8	¾ in. to No. 8 (9.5 to 2.36 mm)	...	...	...	...	...	...	...	...	100	85 to 100	10 to 30	0 to 10	0 to 5

**Table 3. Grading and nomenclature used in the analysis of ASTM C33.**

Cement (Type I) particle size ( $\mu\text{m}$ )	Percent passing (%)
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7.5	22
15	46
30	74
45	88
80	100

Fine Aggregate particle size (in.)	Percent passing (%)
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0.0059	6
0.0118	20
0.0236	42
0.0465	67
0.0929	90
0.187	97
0.374	100

Sieve size (in.)	<u>1H</u>	Percent passing (%)		<u>1M</u>	<u>1ASIS</u>
		<u>1L</u>	<u>1LH</u>		
0.75	0.01	5	5	0.01	2.5
1.5	0.01	15	15	0.01	7.5
2.5	25	60	42	60	42
3.5	90	99.9	90	99.9	95
4	100	100	100	100	100

Sieve size (in.)	<u>2H</u>	Percent passing (%)		<u>2M</u>	<u>2ASIS</u>
		<u>2L</u>	<u>2LH</u>		
0.75	0.01	5	5	0.01	2.5
1.5	0.01	15	15	0.01	7.5
2	35	70	52	70	52
2.5	90	99.9	90	99.9	95
3	100	100	100	100	100

Sieve size (in.)	<u>3H</u>	Percent passing (%)		<u>3M</u>	<u>3ASIS</u>
		<u>3L</u>	<u>3LH</u>		
0.5	0.01	5	5	0.01	2.5
1	0.01	15	15	0.01	7.5
1.5	35	70	52	70	52
2	90	99.9	90	99.9	95
2.5	100	100	100	100	100

**Table 3.      Gradings and nomenclature used in the analysis of ASTM C33  
Continued.**

Sieve size (in.)	Percent passing (%)				
	<u>357H</u>	<u>357L</u>	<u>357LH</u>	<u>357M</u>	<u>357ASIS</u>
0.187	0.01	5	5	0.01	2.5
0.5	10	30	30	0.01	20
1	35	70	52	70	52
2	90	99.9	90	99.9	97.5
2.5	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>4H</u>	<u>4L</u>	<u>4LH</u>	<u>4M</u>	<u>4ASIS</u>
0.375	0.01	5	5	0.01	2.5
0.75	0.01	15	15	0.01	7.5
1	20	55	37	55	37
1.5	90	99.9	90	99.9	95
2	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>467H</u>	<u>467L</u>	<u>467LH</u>	<u>467M</u>	<u>467ASIS</u>
0.187	0.01	5	5	0.01	2.5
0.375	10	30	30	10	20
0.75	35	70	52	70	52
1.5	95	99.9	95	99.9	97.5
2	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>5H</u>	<u>5L</u>	<u>5LH</u>	<u>5M</u>	<u>5ASIS</u>
0.375	0.01	5	5	0.01	2.5
0.5	0.01	10	10	0.01	5
0.75	20	55	37	55	37
1	90	99.9	90	99.9	95
1.5	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>56H</u>	<u>56L</u>	<u>56LH</u>	<u>56M</u>	<u>56ASIS</u>
0.187	0.01	5	5	0.01	2.5
0.375	0.01	15	15	0.01	7.5
0.5	10	40	25	10	25
0.75	40	85	62	85	62
1	90	99.9	90	99.9	95
1.5	100	100	100	100	100



**Table 3. Gradings and nomenclature used in the analysis of ASTM C33  
Continued.**

Sieve size (in.)	Percent passing (%)				
	<u>57H</u>	<u>57L</u>	<u>57LH</u>	<u>57M</u>	<u>57ASIS</u>
0.0929	0.01	5	5	0.01	2.5
0.187	0.01	10	10	0.01	5
0.5	25	60	42	60	42
1	90	99.9	90	99.9	97.5
1.5	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>6H</u>	<u>6L</u>	<u>6LH</u>	<u>6M</u>	<u>6ASIS</u>
0.187	0.01	5	5	0.01	2.5
0.375	0.01	15	15	0.01	7.5
0.5	20	55	42	55	42
0.75	90	99.9	90	99.9	95
1	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>67H</u>	<u>67L</u>	<u>67LH</u>	<u>67M</u>	<u>67ASIS</u>
0.0929	0.01	5	5	0.01	2.5
0.187	0.01	10	10	0.01	5
0.375	20	55	42	55	42
0.75	90	99.9	90	99.9	95
1	100	100	100	100	100

Sieve size (in.)	Percent passing (%)				
	<u>7H</u>	<u>7L</u>	<u>7LH</u>	<u>7M</u>	<u>7ASIS</u>
0.0929	0.01	5	5	0.01	2.5
0.187	0.01	15	15	0.01	5
0.375	40	70	55	70	42
0.5	90	99.9	90	99.9	95
0.75	100	100	100	100	100

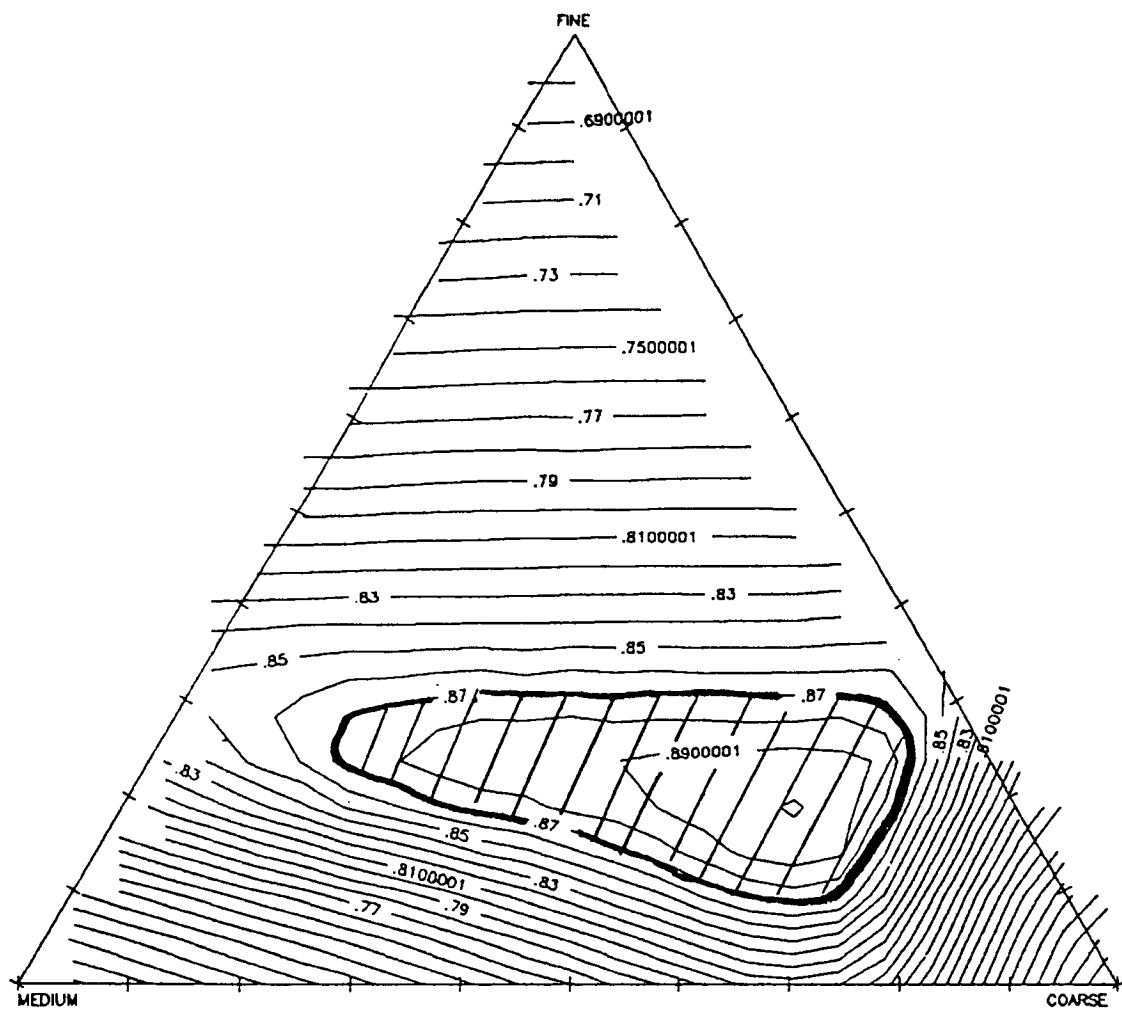
Sieve size (in.)	Percent passing (%)				
	<u>8H</u>	<u>8L</u>	<u>8LH</u>	<u>8M</u>	<u>8ASIS</u>
0.0465	0.01	5	5	0.01	2.5
0.0929	0.01	10	10	0.01	5
0.187	10	30	20	30	20
0.375	85	99.9	85	99.9	92
0.5	100	100	100	100	100

therefore in poorer concretes. These poor packing density characteristics within a size number designation include combinations which result in (1) a noticeably lower maximum packing density than other combinations, (2) very small regions of comparable packing density, and/or (3) sharp gradients in packing density in the directions of increasing/decreasing volume percent of coarse or fine aggregate. This final characteristic would result in very little tolerance for error in aggregate proportioning during the mixing process. Small deviations from the prescribed proportions would lead to large changes in concrete packing density and therefore initial and final concrete properties.

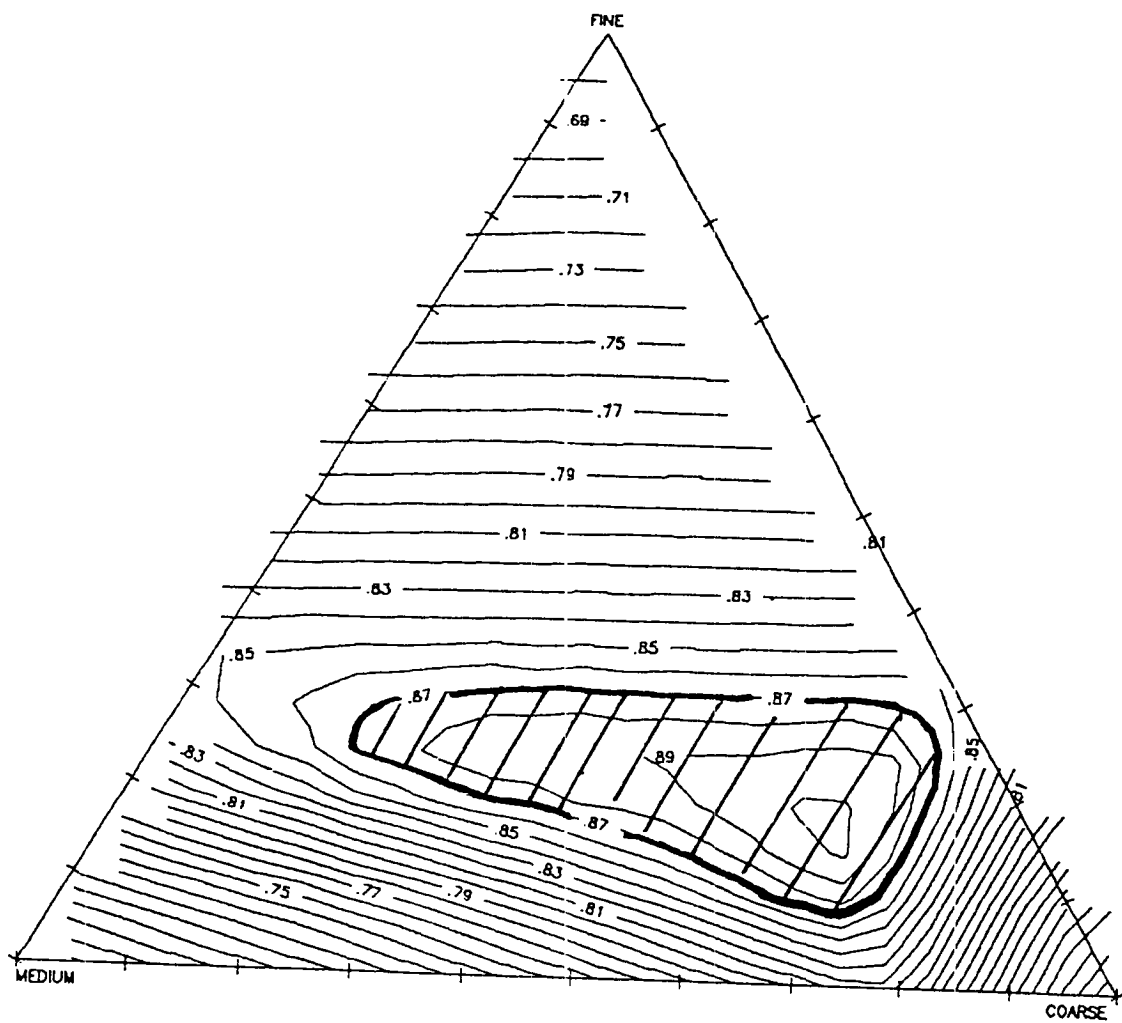
An encouraging outcome of the packing model output is that there appears to be, for the components under investigation, a certain arbitrary level of packing density which is the same in value, and roughly the same in area and location, for all of the combinations within a size number designation. An example of this phenomenon is demonstrated by comparing the shaded regions of Fig. 4, Fig. 5, and Fig. 6. These represent the trilinear diagrams based on combinations 8H, 8LH, and 8M, respectively. Notice that while the maximum packing density value, the area corresponding to that maximum packing density, and the position of the maximum packing density are different for all three combinations, the density plateau labeled 0.87 is generally the same in shape, area, and position for the three (specifically, combinations 8H and 8LH have a maximum packing density of 0.90, while combination 8M has a maximum packing density of 0.88). This suggests that in practice 0.87 would be the lowest packing density expected regardless of the proportioning of size fractions in the coarse aggregate size number. Moreover, it is within this large area that many current mixture formulations fall. Only the characteristics of the packing densities above this "base level" appear to be affected by the various combinations examined here. Thus, while the findings of this investigation should improve the use of coarse aggregates in concrete, it is reassuring to have found that the packing model helps to explain the generally acceptable results obtained employing the current ASTM C33 size number gradings.

The findings of this investigation are presented below for each of the size number designations listed in ASTM C33 and are summarized later in Table 3. There is not a general trend which pervades all the size numbers, so each size number must be analyzed and revised on a case-by-case basis. It must be understood that the analysis given and revisions recommended below are of a general nature, and that specific numerical revisions to ASTM C33 are not suggested. This is because this investigation was concerned only with the packing density characteristics of concrete as relates to ASTM C33. Aggregate production capabilities and economics, although they play a significant role, were not investigated. Therefore, specific recommendations for changes to the existing grading limits in Table 2 of ASTM C33 will have to be formulated in the appropriate forum, viz. ASTM Subcommittee C09.03.05.

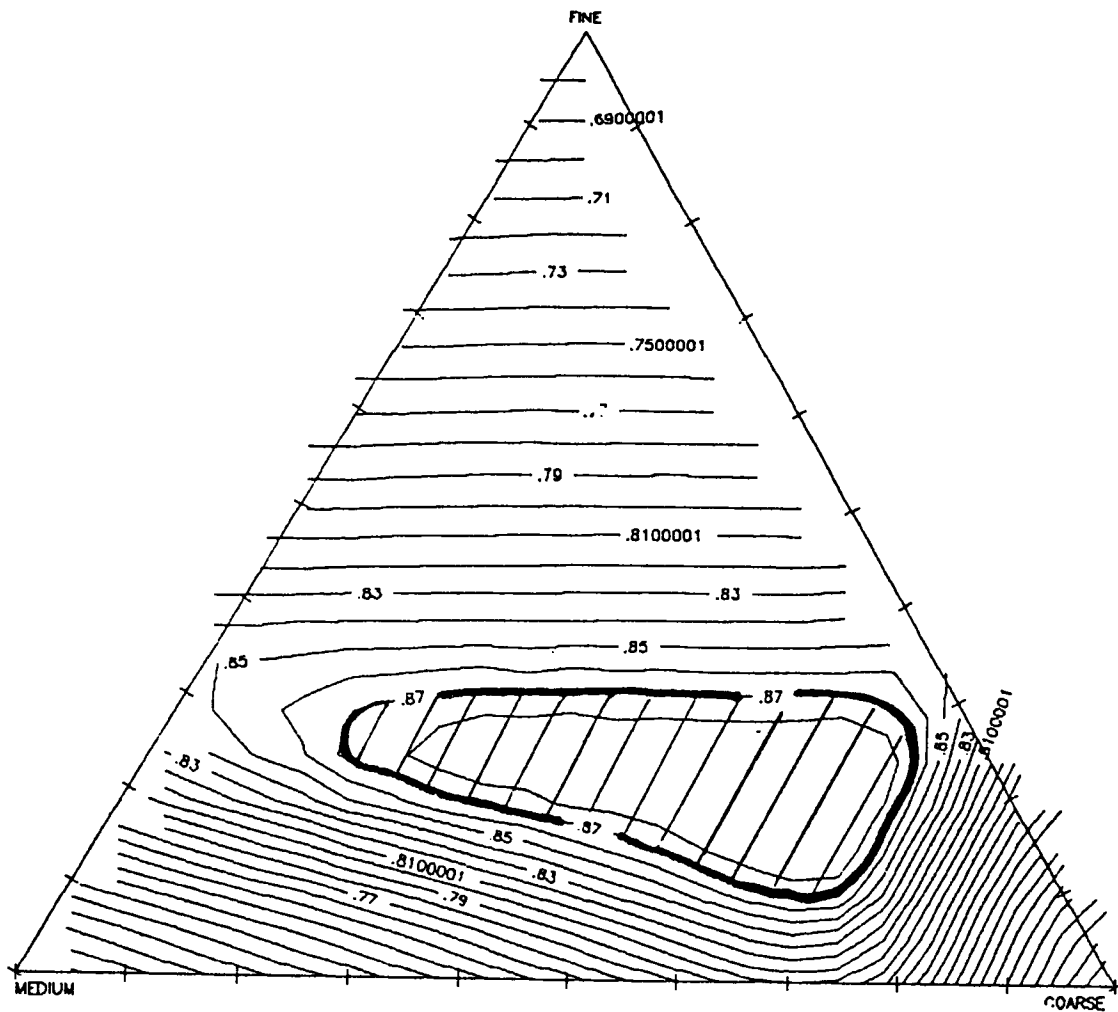
It should be noted for the discussion below that the packing densities labeled on the trilinear diagrams reproduced in the Appendix for each size number are for comparative purposes only. They do not necessarily represent the absolute packing densities for each isodensity line.



**Figure 4. Grading combination 8H.**



**Figure 5. Grading combination 8LH.**



**Figure 6. Grading combination 8M.**

**Size Number 1**—Although all combinations result in a maximum packing density of greater than 0.92, it was determined that coarse aggregate combinations emphasizing (1) the largest aggregates (refer to combination 1H in the App.), or (2) the medium-sized aggregates (1M), would result in concretes with much smaller areas of peak density when compared to other combinations. Therefore, revisions to the grading requirements for size number 1 to avoid emphasis on gradings such as 1H or 1M is recommended. This would allow for greater variations in proportioning in the field without deviating from the region of maximum packing density.

**Size Number 2**—The finding for this size number is similar to that for size number 1. Therefore, an appropriate revision to avoid excessive volume fractions of either the largest (2H) or the medium-sized (2M) aggregates within this size number designation is suggested.

**Size Number 3**—In this case, combinations 3H and 3M produced undesirable density characteristics. Specifically, the area of the maximum packing density of 0.92 is much smaller for these combinations than for 3L, 3LH, or 3ASIS. Therefore, revisions made to avoid gradings such as 3H or 3M would result in concretes with better packing density characteristics.

**Size Number 357**—This size number had no combinations exhibiting truly "poor" packing characteristics. However, the gradings correlating to 357ASIS and 357L possess a larger area of maximum packing density. Revisions to the gradings to reflect that finding are therefore warranted. Notice that 357LH results in a maximum packing density plateau which is rather narrow, and thus sensitive to variations in fine or coarse aggregate volume fractions. Such a grading should be avoided, if possible.

**Size Number 4**—In this size number designation, combination 4LH exhibits the best packing density characteristics (largest area of maximum packing), while 4M and 4ASIS are not as good. Therefore, the gradings might be revised to minimize the changes for obtaining a grading similar to 4M or 4ASIS. Although all of the size combinations within size number 4 are different, the differences are not significant.

**Size Number 467**—Combinations 467ASIS and 467L are better than the other combinations. They have a maximum packing density of greater than 0.92, and also have this packing density over a large area. Combination 467H also achieves this degree of packing, but only in a very small region. Finally, combinations 467LH and 467M each have maximum packing densities less than 0.91 (notice that the highest isodensity line on the diagrams for these combinations is 0.90, indicating that the packing density never reaches the next plateau of 0.91). Therefore, it is recommended that the gradings within this size number be revised in a manner to emphasize those gradings which produce concrete mixtures with significantly higher maximum packing density, namely 467ASIS and 467L.

**Size Number 5**—In this case, combination 5ASIS would produce a concrete with a markedly higher maximum packing density than other combinations. Therefore, tightening the current grading so that this finding is translated into practice is suggested.

**Size Number 56**—Combinations 56L, 56LH, and 56ASIS possess a maximum packing density shown of greater than 0.92, which is significantly better than for the other combinations. Restricting the coarse aggregate grading possibilities to reflect grading combinations 56L, 56LH, and/or 56ASIS would therefore result in improved concretes.

**Size Number 57**—Combinations 57L, 57LH, and 57ASIS possess a maximum packing density shown of greater than 0.92, which is significantly better than for the other combinations. Restricting the coarse aggregate grading possibilities to reflect grading combinations 57L, 57LH, and/or 57ASIS would therefore result in improved concretes.

**Size Number 6**—6ASIS and 6LH provided better packing by a small margin. Avoidance of a great majority of the aggregate coming from either the largest size (6H), the smallest size (6L), or the medium-size (6M) only is warranted because this results in lower maximum packing density being achieved.

**Size Number 67**—Combinations 67ASIS and 67LH again provided better packing characteristics (a maximum packing density greater than 0.92) as was the case for size number 6. Also as in size number 6, combinations such as 67H, 67L, and 67M should be avoided (maximum packing density less than 0.91) through appropriate specification revisions.

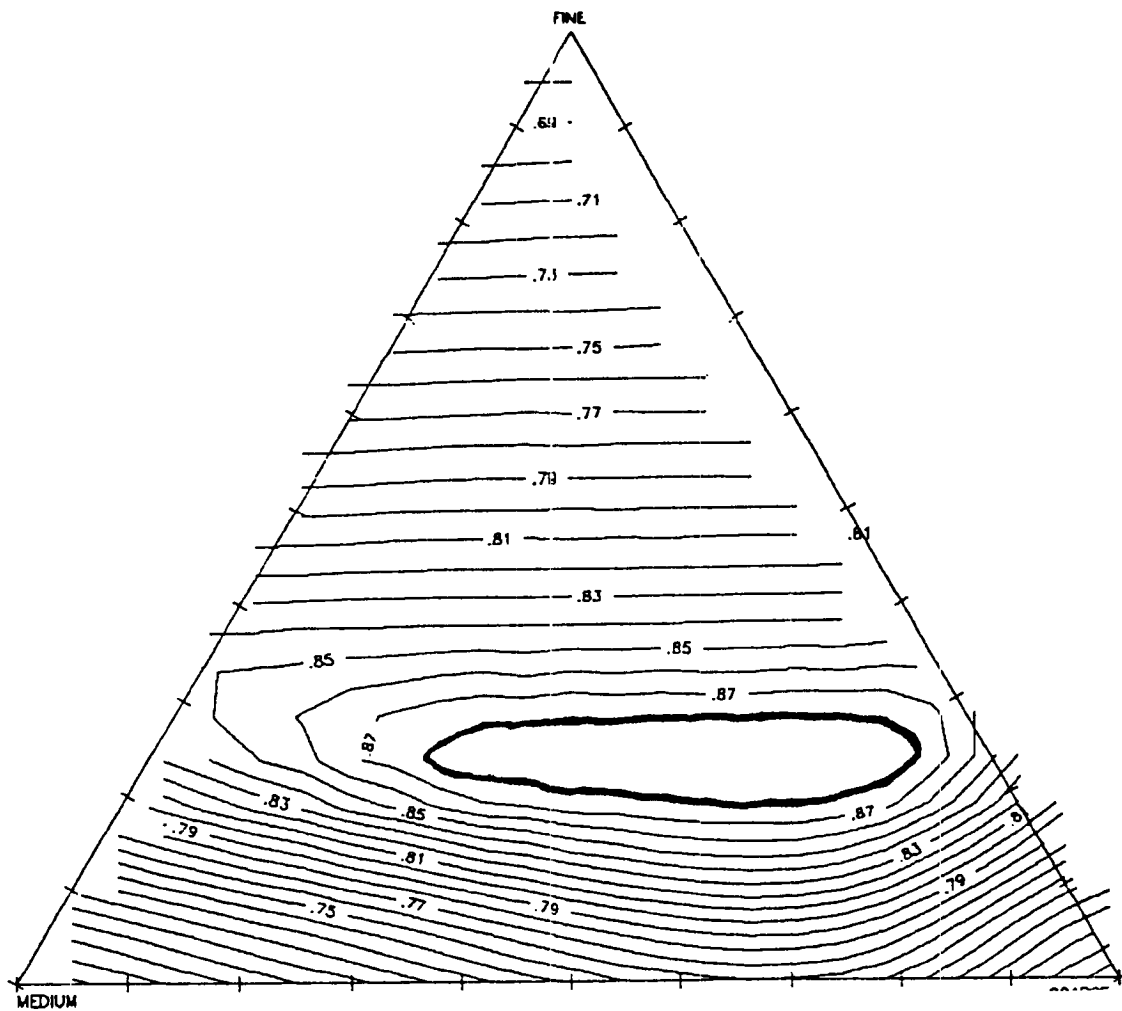
**Size Number 7**—This size number designation presented the only case where all five combinations tested result in very similar packing diagrams, with 7ASIS being only slightly preferable based on its slightly larger area of maximum packing density. Therefore, the only revision recommended for this size number designation would be to emphasize grading 7ASIS, but revisions within this size number will not yield benefits as great as is the case in others.

**Size Number 8**—Combination 8L is a far worse mixture, with respect to packing density, than the others tested within this size number designation. This combination results in a very narrow packing density plateau that is not tolerant to increasing or decreasing coarse aggregate or fine aggregate volume fractions. Combination 8L is shown in Fig. 7 and helps to illustrate how all of the above-mentioned recommended revisions were derived. Fig. 8 represents grading combination 8H. It can easily be seen from the shaded regions of Fig. 7 and Fig. 8 that combination 8H results in a larger area of high packing density which is more tolerant to variations in coarse and fine aggregate volume fractions. 8H also results in a higher peak (maximum) density than does 8L. For this size number overall, gradings similar to 8H, 8LH, and 8ASIS are preferable, with 8LH being the most preferable due to its larger area of maximum packing density.<sup>7</sup>

The recommendations listed above comprise the complete list of recommended revisions to the coarse aggregate grading requirements of ASTM C33. The discussions above are summarized in Table 4, including the maximum packing density for each combination, the qualitatively estimated sensitivity to fine/coarse aggregate volume fraction variations

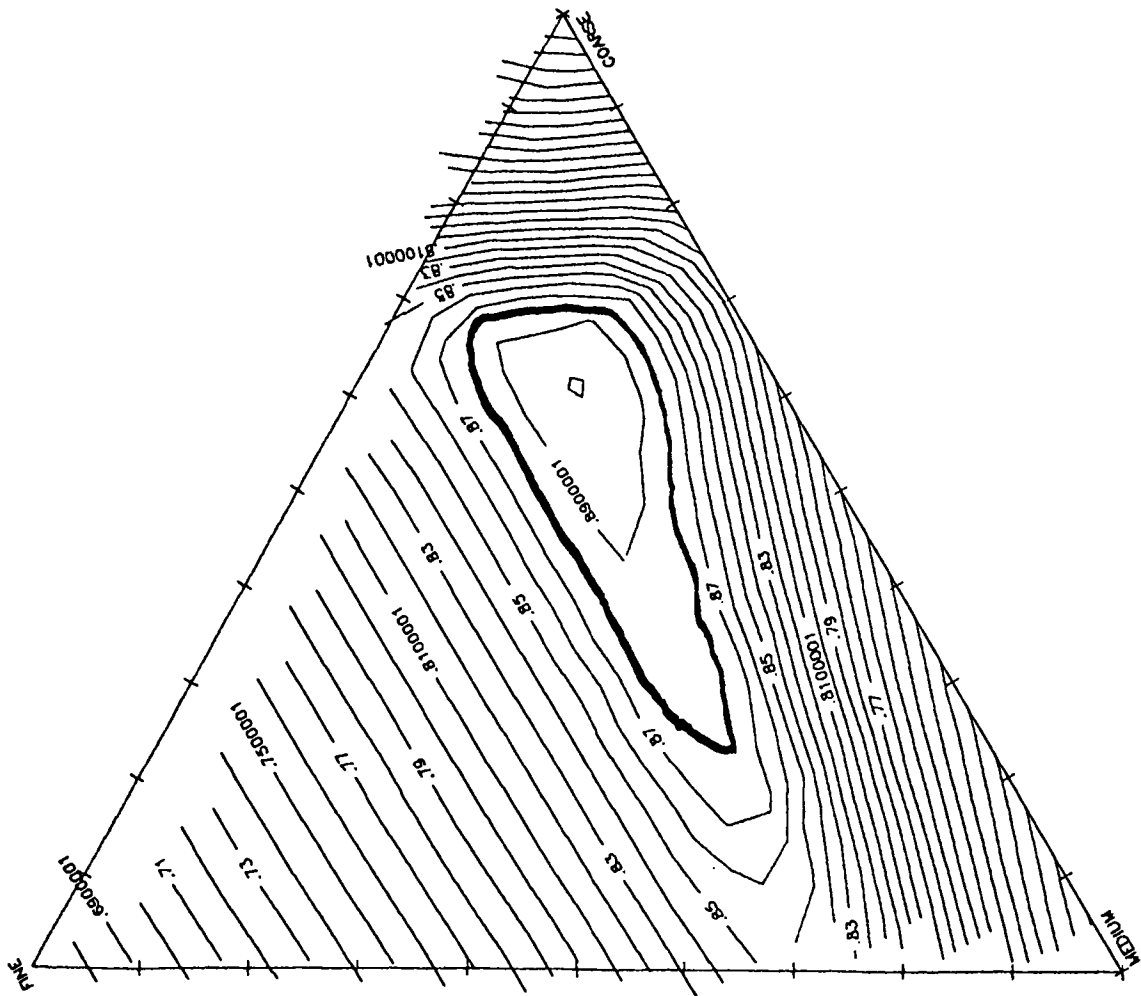
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<sup>7</sup>See note 6.



**Figure 7.** Example of trilinear diagram with low maximum packing density and high sensitivity to coarse/fine aggregate variations (combination 8L).





**Figure 8.** Example of trilinear diagram with high maximum packing density and low sensitivity to coarse/fine aggregate variations (combination 8H).

**Table 4. Summary of results from analysis of ASTM C33.**

Size number designation	Maximum packing density	Sensitivity to fine/coarse volume fraction variations (1=no, 2=yes)	Relative area of maximum packing density within size number group (1=large, 5=small)
1H	0.92	1	4
1L	0.92	1	1
1LH	0.92	1	3
1M	0.92	1	4
1ASIS	0.92	1	1
2H	0.92	1	4
2L	0.92	1	1
2LH	0.92	1	1
2M	0.92	1	4
2ASIS	0.92	1	1
3H	0.92	1	3
3L	0.92	1	1
3LH	0.92	1	1
3M	0.92	1	4
3ASIS	0.92	1	1
357H	0.92	1	4
357L	0.92	1	2
357LH	0.92	2	4
357M	0.92	1	
357ASIS	0.92	1	2
4H	0.92	1	4
4L	0.92	1	3
4LH	0.92	1	2
4M	0.92	1	5
4ASIS	0.92	1	5
467H	0.92	1	5
467L	0.92	1	3
467LH	0.90	1	1
467M	0.90	1	1
467ASIS	0.92	1	3
5H	0.90	1	2
5L	0.90	1	2
5LH	0.90	1	2

**Table 4. Summary of results from analysis of ASTM C33 Continued.**

Size number designation	Maximum packing density	Sensitivity to fine/coarse volume fraction variations (1=no, 2=yes)	Relative area of maximum packing density within size number group (1=large, 5=small)
5M	0.90	1	2
5ASIS	0.92	1	3
56H	0.90	1	1
56L	0.92	1	3
56LH	0.92	1	3
56M	0.90	1	1
56ASIS	0.92	1	3
57H	0.90	1	2
57L	0.92	1	4
57LH	0.92	1	3
57M	0.90	1	2
57ASIS	0.92	1	3
57H	0.92	1	4
57L	0.92	1	1
57LH	0.92	1	1
57M	0.92	1	4
57ASIS	0.92	1	1
6H	0.90	1	2
6L	0.90	1	2
6LH	0.92	1	3
6M	0.90	1	3
6ASIS	0.92	1	3
67H	0.90	1	3
67L	0.90	1	3
67LH	0.92	1	5
67M	0.90	1	3
67ASIS	0.92	1	4
7H	0.90	1	3
7L	0.90	1	4
7LH	0.90	1	3

**Table 4. Summary of results from analysis of ASTM C33 Continued.**

Size number designation	Maximum packing density	Sensitivity to fine/coarse volume fraction variations (1=no, 2=yes)	Relative area of maximum packing density within size number group (1=large, 5=small)
7M	0.90	2	4
7ASIS	0.90	1	3
8H	0.90	1	5
8L	0.88	2	1
8LH	0.90	1	4
8M	0.88	1	5
8ASIS	0.90	1	4

(although only combination 8L is exceptionally sensitive to such variations), and the relative area of maximum packing density within a size number group. The numeric values assigned in Table 4 are based on primarily qualitative observations of the trilinear packing diagrams given in the App.

## **Recommendations on Standard Specifications and Test Methods**

The following section discusses work completed under this contract which has resulted in general recommendations regarding standard specifications, practices, or test methods in ASTM and ACI. Specific revisions, such as those detailed in the previous section of this report, are not provided with regard to these specifications because it has been judged that enough reliable, precise data have not yet been generated to warrant this. However, the research has produced results which obviously relate, and in some way affect, the following standards. This general discussion is proposed to enhance either the use, understanding, or future research of these topics in relation to these standards.

### *ASTM C856:*

#### *Standard Practice for Petrographic Examination of Hardened Concrete*

The comments made here are primarily to alert ASTM Subcommittee C09.02.06, having technical charge of this Standard Practice, to the possibilities that may exist for future revision or improvements.

Two areas of work have been pursued regarding the petrographic examination of hardened concrete. Both use fluorescent microscopy. One method uses transmitted fluorescent light to analyze the microstructure of hardened concrete. The other method uses reflected fluorescent light to aid the analysis of the microstructure.

The work using transmitted fluorescent microscopy is best summarized in the First Quarterly Report for Year 3 to the Strategic Highway Research Program Project C201, both in the main text and its appendix B recommended "Methodology for Fluorescent Microscopy."<sup>8</sup>

While this technique has reportedly been used successfully in Europe, there remains difficulty in determining the precision and bias of the laboratory method, and there is concern regarding the degree of subjectivity involved in the application of the method. When used by a trained operator, many interesting qualitative aspects of the concrete microstructure may be noted, including estimation of microcracking, estimation of water/cement ratio, and estimates for the relative inhomogeneity of a specimen. Unfortunately, there is no current reliable method for standardizing this method to be independent of the biases of each operator. Also, the description of the microstructure via this method defies rigorous quantification.

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<sup>8</sup>SHRP-201. 1990. First Quarterly Report-Year 3. *Materials Research Laboratory*.

While the preliminary results of the transmitted fluorescent light microscopy were encouraging, problems with the quantification of data, and also problems associated with standardization of sample thicknesses, persist.

Therefore, while this method is of interest to persons undertaking petrographic examination of hardened concrete, it may not be technically mature enough to warrant inclusion in an ASTM standard practice, and therefore it is not recommended for inclusion in ASTM C856, but may be used to supplement ASTM C856 findings.

A second method for analysis of hardened concrete using fluorescent microscopy, using light in a reflected mode, rather than a transmitted mode, also seems promising as a technology which in the future may be included into this standard practice. Sufficient experimentation of this method has not yet been completed at the Materials Research Laboratory to adequately evaluate this procedure, but results from other researchers<sup>9</sup> and technical consultants<sup>10</sup> in this field suggest that this method may be easily implemented and also produce results which can be standardized with regard to the precision and bias of the method. A strong advantage for this method of analysis is that the results obtained are independent of the sample thickness and therefore sample preparation effort is decreased. The only complication associated with this method during this project has been extreme difficulty with impregnation of the concrete samples with a suitable epoxy.

#### *ASTM C330:*

##### *Standard Specification for Lightweight Aggregates for Structural Concrete*

The comments made here are primarily to alert the ASTM Subcommittee having technical charge of this Standard Specification (C09.0306) to the possibilities that may exist for future revision or improvements.

The application of the packing model to the grading of aggregates, fine and coarse, for lightweight aggregate should be as significant as it is in regard to "normal-weight" aggregates in ASTM C33. Due to project time constraints and the fact that the use of the materials discussed in C330 is not within the scope of application of this research, no effort toward a rigorous analysis of this standard has been made. However, it is believed that by employing a similar methodology to C330 as was used to evaluate and revise C33, an improved system of grading would be achieved.

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<sup>9</sup>Mayfield, B. 1990. The quantitative evaluation of the water/cement ratio using fluorescence microscopy. Magazine of Concrete Research. Vol. 42, No. 150.

<sup>10</sup>Abramowitz, M. 1990. A reflected light fluorescence illuminator. American Laboratory. Vol. 22, No. 5.

*ASTM D448:*

*Standard Classification for Sizes of Aggregate for Road and Bridge Construction*

The comments made here are primarily to alert ASTM Subcommittee D04.50, having technical charge of this Standard Classification, to the possibilities that may exist for future revision or improvements.

The application of the packing model to the grading of aggregates for road and bridge construction may result in changes in a way similar to those mentioned in the previous discussion of ASTM C330. Once again, due to time constraints in this project, no particular revisions to this standard are recommended at this time. This is due primarily to the fact that experimental verification of any work done in this area would be required before passing along any recommendations.

The packing program was used to determine gradings within ASTM D448 of maximum self-packing density, and these results are shown in Table 5. Again, the actual gradings were varied in a method similar to those for ASTM C33; this time, however, the aggregate was not "mixed" with sand or cement particles. Therefore, if a high density for the size number designation is required, revisions to the size number designations to reflect the findings shown in Table 5 are appropriate. The gradings are shown in Table 6.

*ASTM C684:*

*Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens*

The comments made here are primarily to alert ASTM Subcommittee C09.02.09, having technical charge of this Test Method, to the possibilities that may exist for future revision or improvements.

The curing and hydration model work of this contract, in its current state, has minimal impact on this standard. If the use of maturity models as heat and strength predictors, such as the CIMS model, increases in the future, however, then inclusion of these types of models into use in this standard might be recommended. It is possible that mathematical and physical modelling of concrete will develop so that many methods other than the Procedures A, B, C, and D currently specified in this standard will be acceptable alternatives. However, at this time, no specific recommendations can be made regarding this standard.

**Table 5. Gradings and nomenclature used in analysis of ASTM D448 (size numbers not shown here are given previously in Table 3 of the ASTM C33 revision).**

Sieve size (in.)	% passing				
	24H	24L	24LH	24M	24ASIS
0.5	0.01	5	5	0.01	2.5
0.75	0.01	10	10	0.01	5
1.5	25	60	42	60	42
2.5	90	99.9	90	99.9	95
3.0	100	100	100	100	100
	68H	68L	68LH	68M	68ASIS
0.0465	0.01	5	5	0.01	2.5
0.0929	0.01	10	10	0.01	5
0.187	5	25	15	25	15
0.375	30	65	48	65	48
0.75	90	99.9	90	99.9	95
1.0	100	100	100	100	100
	78H	78L	78LH	78M	78ASIS
0.0465	0.01	5	5	0.01	2.5
0.0929	0.01	10	10	0.01	5
0.187	5	25	15	25	15
0.375	40	75	58	75	58
0.5	90	99.9	90	99.9	95
0.75	100	100	100	100	100
	89H	89L	89LH	89M	89ASIS
0.0118	0.01	5	5	0.01	2.5
0.0465	0.01	10	10	0.01	5
0.929	5	30	18	30	18
0.187	20	55	38	55	38
0.375	90	99.9	90	99.9	95
0.5	100	100	100	100	100
	9H	9L	9LH	9M	9ASIS
0.0118	0.01	5	5	0.01	2.5
0.0465	0.01	10	10	0.01	5
0.0929	10	40	25	40	25
0.187	85	99.9	85	99.9	93
0.375	100	100	100	100	100



**Table 5. Gradings and nomenclature used in analysis of ASTM D448 (size numbers not shown here are given previously in Table 3 of the ASTM C33 revision) Continued.**

Sieve size (in.)	% passing				
	10H	10L	10LH	10M	10ASIS
0.0059	10	30	30	10	20
0.187	85	99.9	85	99.9	93
0.375	100	100	100	100	100

**Table 6. Self-packing densities for various gradings currently allowed within ASTM D448.**

	<b>H</b>	<b>L</b>	<b>LH</b>	<b>M</b>	<b>ASIS</b>
1	0.622	<b>0.677</b>	0.639	0.622	0.659
2	0.620	<b>0.663</b>	<b>0.663</b>	0.620	<b>0.663</b>
24	0.642	0.683	<b>0.696</b>	0.642	0.633
3	0.622	<b>0.680</b>	<b>0.680</b>	0.620	<b>0.680</b>
357	0.634	0.673	0.643	0.628	<b>0.680</b>
4	0.622	0.649	<b>0.680</b>	0.621	0.621
467	0.632	<b>0.680</b>	0.638	0.630	<b>0.680</b>
5	0.616	0.620	0.620	0.616	<b>0.665</b>
56	0.625	<b>0.696</b>	0.692	0.627	<b>0.696</b>
57	0.630	0.678	0.659	0.627	<b>0.680</b>
6	0.622	0.649	<b>0.679</b>	0.621	0.669
67	0.625	0.674	<b>0.680</b>	0.625	0.678
68	0.662	0.706	0.696	0.658	<b>0.715</b>
7	0.623	0.675	<b>0.680</b>	0.623	0.675
78	0.654	0.714	0.708	0.652	<b>0.715</b>
8	0.625	<b>0.680</b>	0.658	0.625	<b>0.680</b>
89	0.671	0.694	0.673	0.669	<b>0.708</b>
9	0.658	0.683	0.662	0.654	<b>0.691</b>
10	0.612	0.608	0.606	<b>0.613</b>	0.608

Note: Gradings within a size number designation resulting in highest self-packing density are shown in boldtype.

*ASTM C918:*

*Standard Test Method for Developing Early-Age Compression Test Values and Projecting Later-Age Strengths*

The comments made here are primarily to alert ASTM Subcommittee C09.02.09, having technical charge of this Test Method, to the possibilities that may exist for future revision or improvements.

For reasons similar to those discussed in the section pertaining to ASTM C684, there are no current recommended revisions to this standard. However, as modelling of strength gain is extended, improved, and experimentally verified, such models may be incorporated into standards such as this one.

*ACI 211.1:*

*Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*

The comments made here are primarily to alert ACI Committee 211, having technical charge of this Standard Practice, to the possibilities that may exist for future revision or improvements.

It is suggested that the revisions to ASTM C33 may affect the weights and volumes represented in some of the tables of this standard. The existing tables were formulated based on the use of aggregates fitting the requirements of ASTM C33. The revisions to C33 recommended earlier in this report may substantially increase the average packing density so that the weights mentioned in ACI require slight revision. It is also suggested that the text of the packing report be kept in mind when remedial procedures for trial batches are made. In many instances slump, segregation, and bleeding may be altered by varying the choice of aggregate grading rather than adjusting water/cement ratio or some other remedial procedure. However, the revisions to ASTM C33 are made based on considerations of dry packing density only. The effects of mix water and air-entrainment need further study before a direct method for concrete proportioning is advised.

*ACI 308:*

*Standard Practice for Curing Concrete*

The comments made here are primarily to alert ACI Committee 308, having technical charge of this Standard Practice, to the possibilities that may exist for future revision or improvements.

While the curing and hydration models developed by this research are not yet extensive enough to be included specifically in this standard practice, it is suggested that models such as CIMS will come to great use in establishing appropriate curing methods for given environmental conditions, especially in the choice of appropriate insulation, curing temperature, or curing compound. Generation of curing tables based on an acceptable

curing model would prove beneficial to the highway engineer, provided variables such as insulation and temperature (as mentioned above), are taken into account.

#### *ACI 305:*

##### *Hot Weather Concreting*

The comments made here are primarily to alert ACI Committee 305, having technical charge of this Standard Practice, to the possibilities that may exist for future revision or improvements.

Based on the output of curing/hydration models, curing tables, similar to those shown in previous quarterly reports<sup>11</sup> and generated from output of the CIMS model, may be developed which relate concrete behavior and environmental conditions to general longer term concrete microstructure and mechanical and durability characteristics. These tables might be appended to the existing ACI 305 recommended practice. Thus, they will serve as an additional source of information to be used by the concrete practitioner to aid in the mixing and placing of concrete under hot weather conditions.

Unfortunately, the CIMS model has not been able to reliably produce output to be included into ACI 305 at this time.

#### *ACI 306:*

##### *Cold Weather Concreting*

The comments made here are primarily to alert ACI Committee 306, having technical charge of this Standard Practice, to the possibilities that may exist for future revision or improvements.

For reasons similar to those cited above for ACI 305, curing tables might, in the future, be included as appendices to this ACI recommended practice for cold weather concreting. However, at this point in time, a sufficient number of such curing tables have not been generated due to the lack of a reliable curing and hydration model.

## **Discussion of Slump and Permeability**

The work done on slump and viscosity relates to the standards and specifications in a general way. It appears that the slump test gives the concrete practitioner certain information vital to the optimal use of the product. Devices such as the drop table or the Vebe test, however, could provide additional information regarding workability that might be better understood. It should be noted that the drop table was previously incorporated into a standardized test (ASTM C124) which has been discontinued. It is recommended that the Subcommittee in charge of ASTM C124 reconsider the use of such a standardized

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<sup>11</sup>SHRP-201. 1989. Second Quarterly Report-Year 2. *Materials Research Laboratory*.

test, using the discussions on thixotropy and concrete rheology generated as a tool during the analysis.<sup>12</sup>

Work in permeability has included work on a chloride permeability test as well as a "pulse pressure" method for general concrete permeability.<sup>13</sup> The pulse pressure testing method should be pursued as a potential standardized test. It is important to note the method's limitations. This method is only practical for concretes with permeabilities in the microdarcy or greater range, due to the time (up to several weeks) required for testing less permeable concretes.

The information on precision and bias for the chloride permeability test was obtained too late in the project for sufficient, rigorous review, but the method appears feasible and useful. It is recommended that SHRP officials relate this information to the appropriate governing bodies of ASTM.

## Summary

Specifications, test methods, and standard practices for concrete have been reviewed, evaluated, and revised in light of work completed in SHRP's contract C-201. The recommended revisions to ASTM and ACI have been presented with the corresponding reasons for changing them, and these recommendations take two forms: specific revisions to existing standards and specifications, and general recommendations to existing standards and specifications. Most of the changes are related to the packing model and the curing/hydration models. At this time, no new standard specifications, test methods, or recommended practices are forthcoming. However, the potential for several do exist based on work completed, and continuation of investigation in those areas is recommended.

Additional research has been suggested where appropriate, and general recommendations highlight areas where future work might be best concentrated.

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<sup>12</sup>See note 1.

<sup>13</sup>Roy, D.M. 1993. Development of Transient Permeability Theory and Apparatus for Measurements of Cementitious Materials. *Strategic Highway Research Program*. SHRP-C-628.

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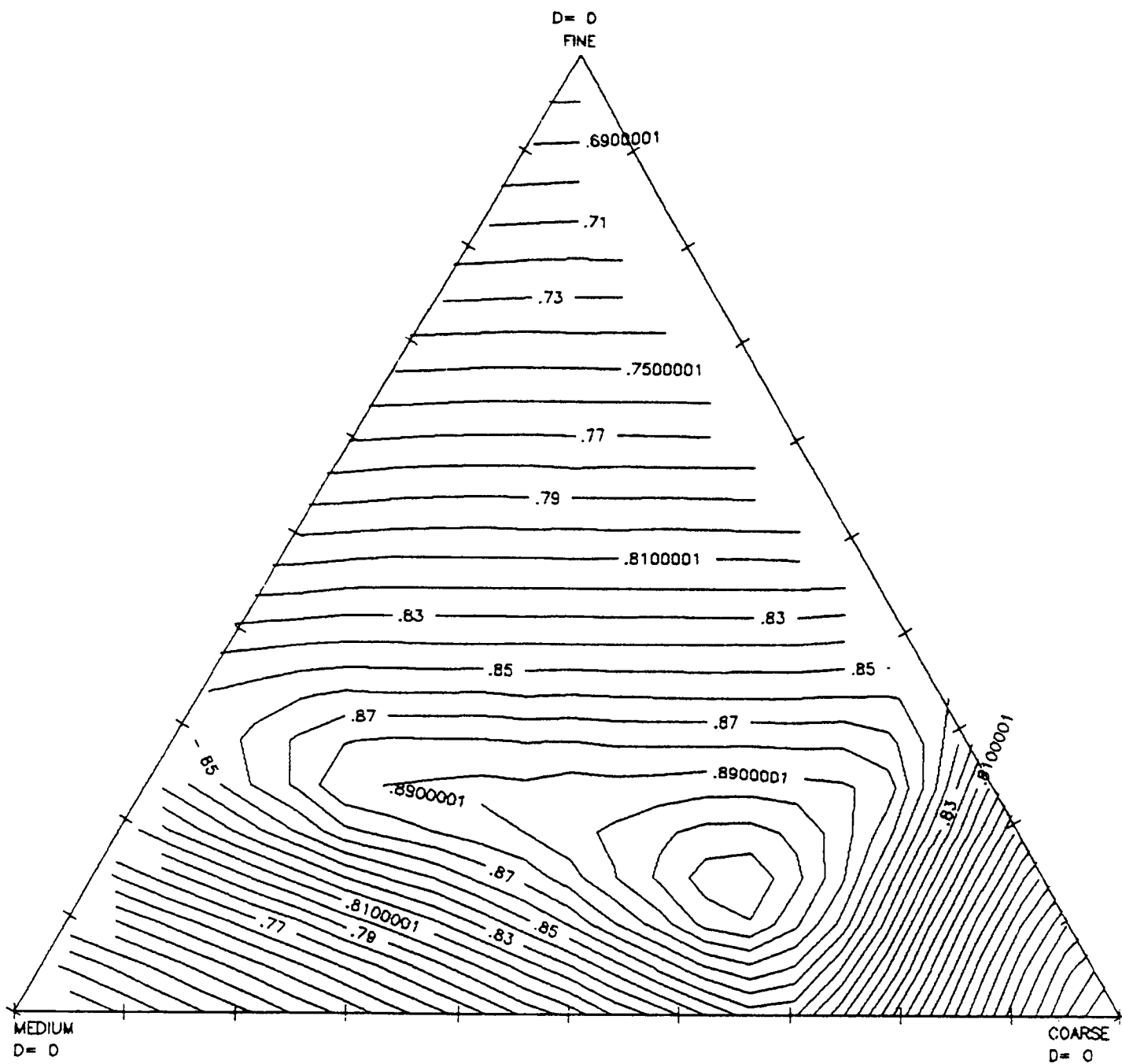
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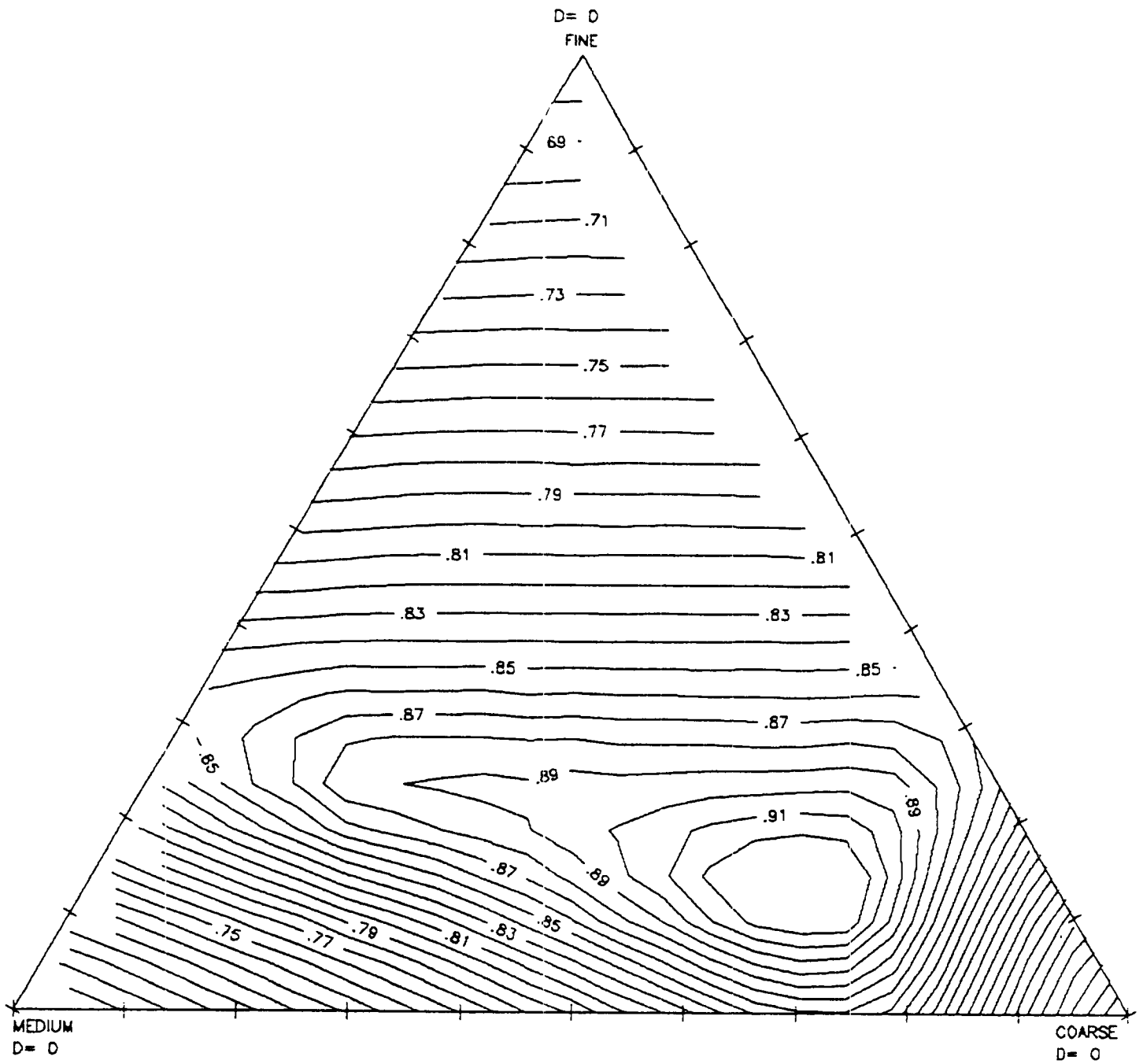
## **Appendix**

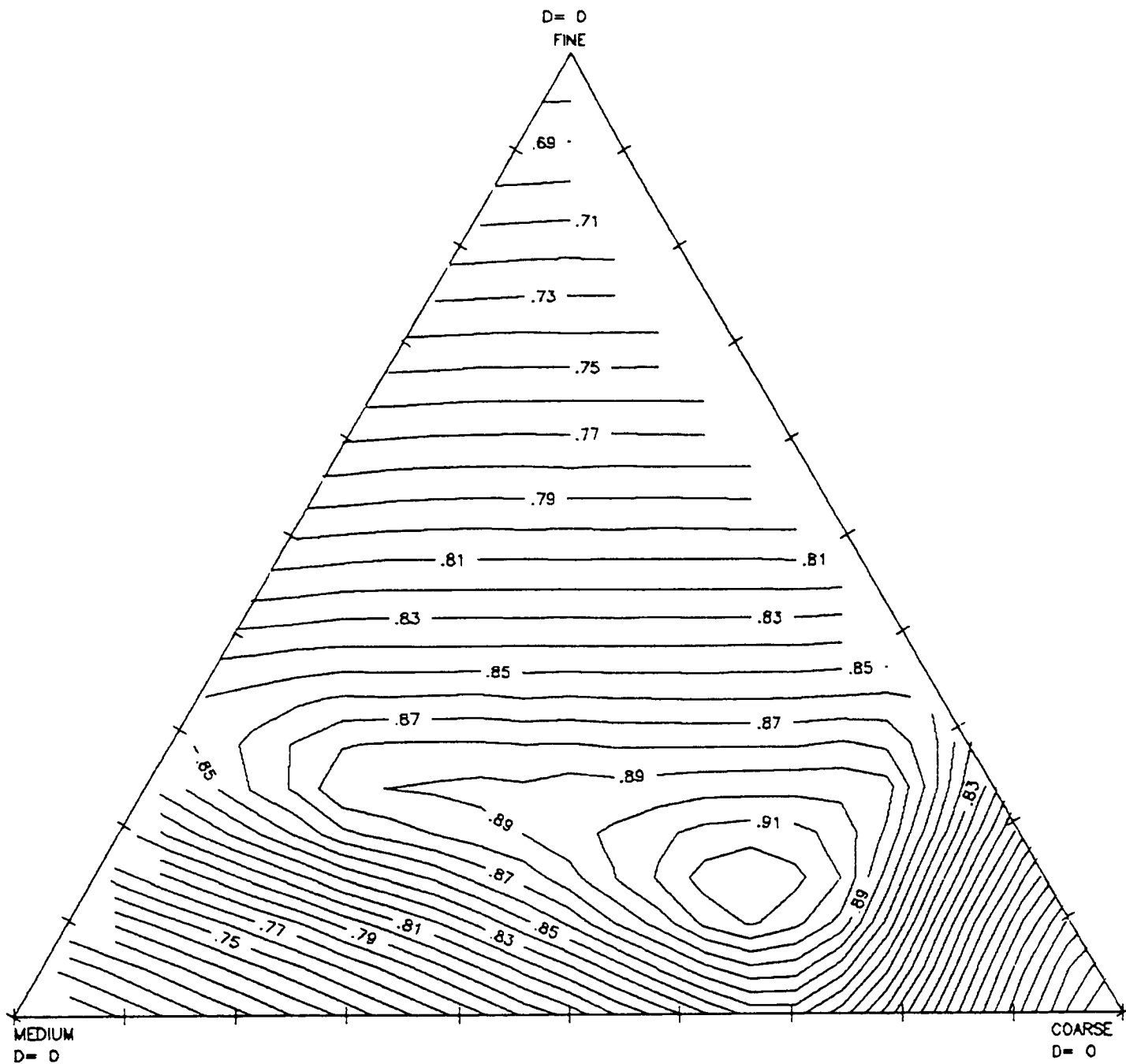
### **Trilinear Diagrams Used in the Analysis of ASTM C33**



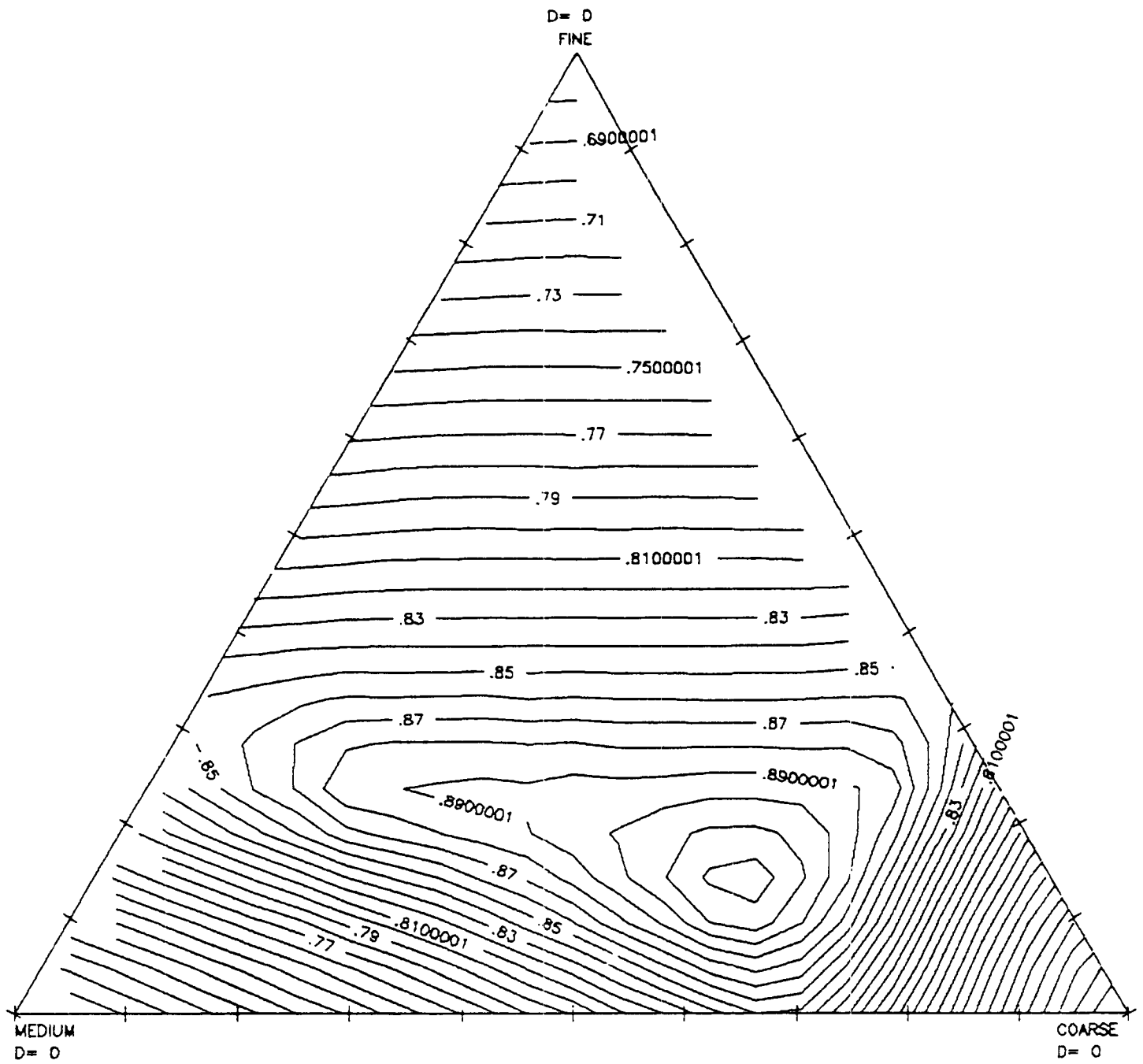


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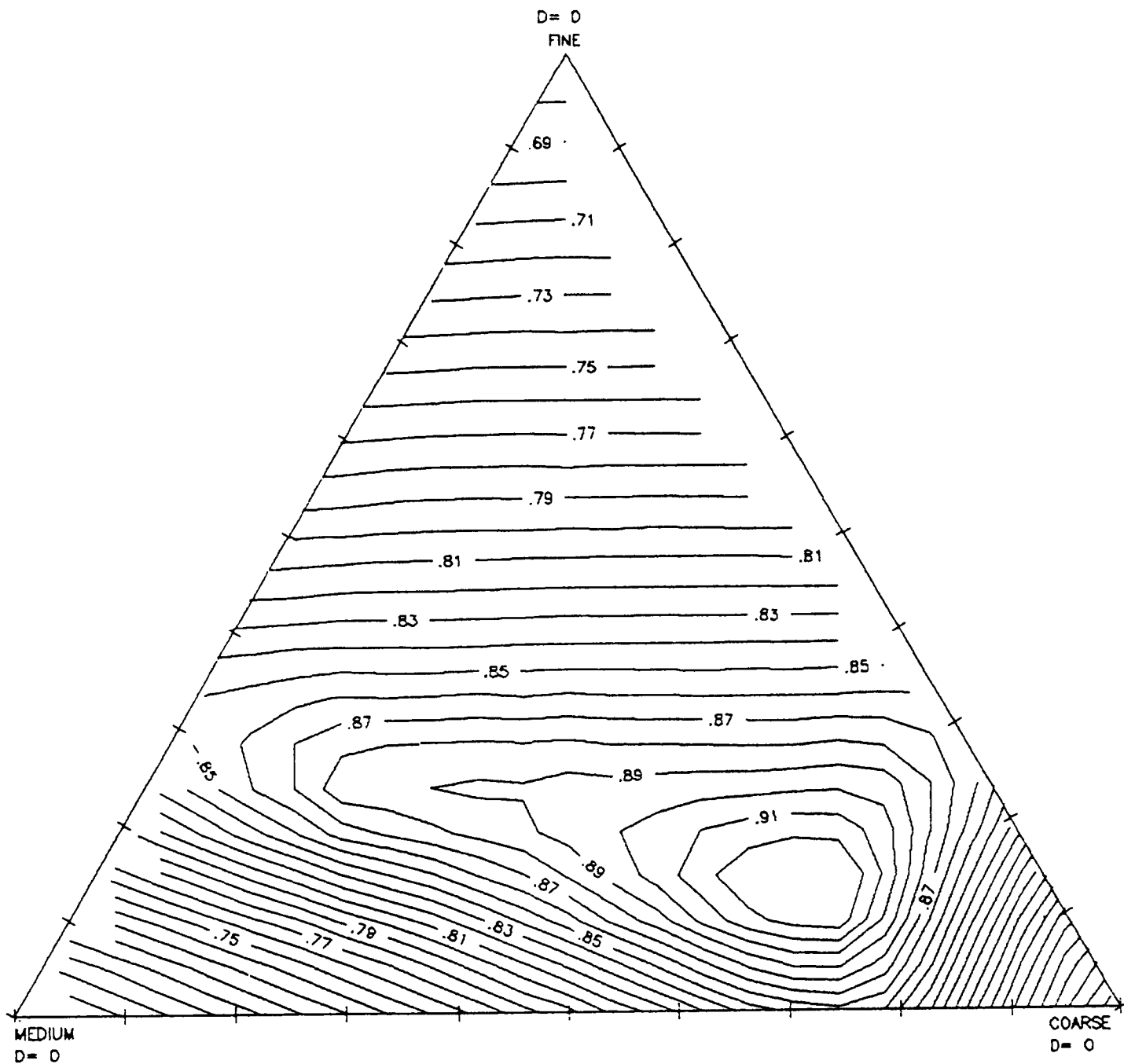




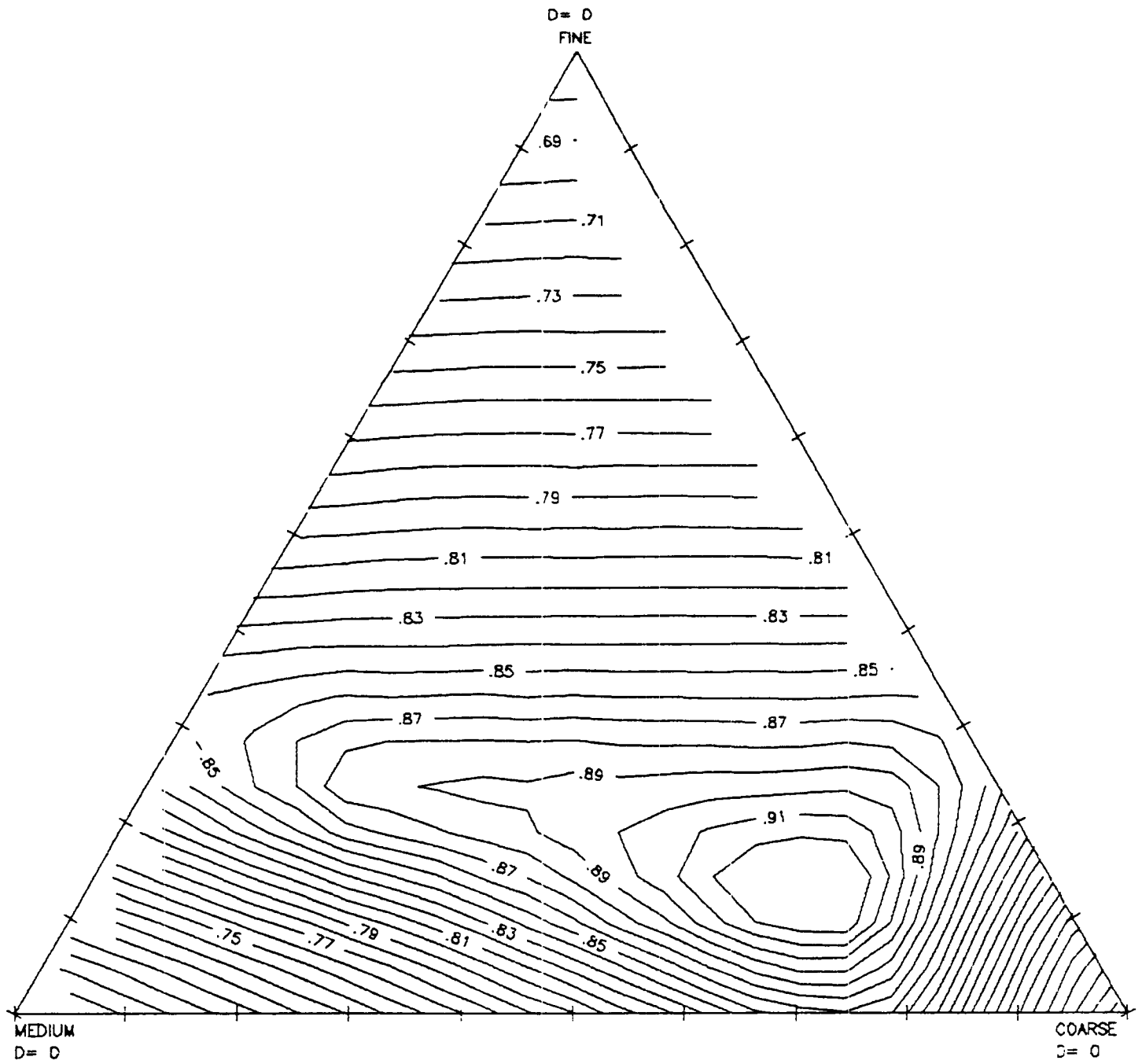
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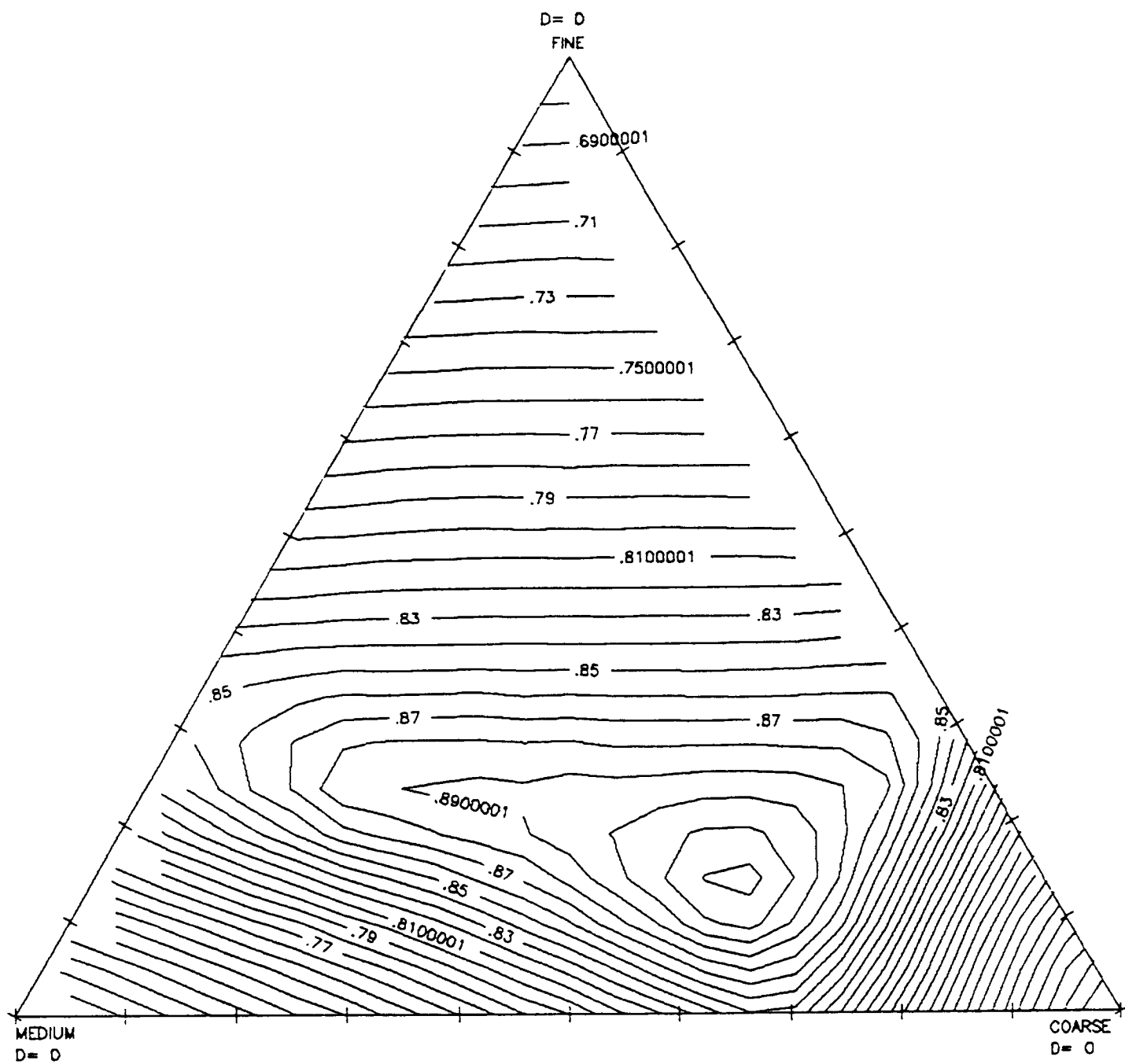
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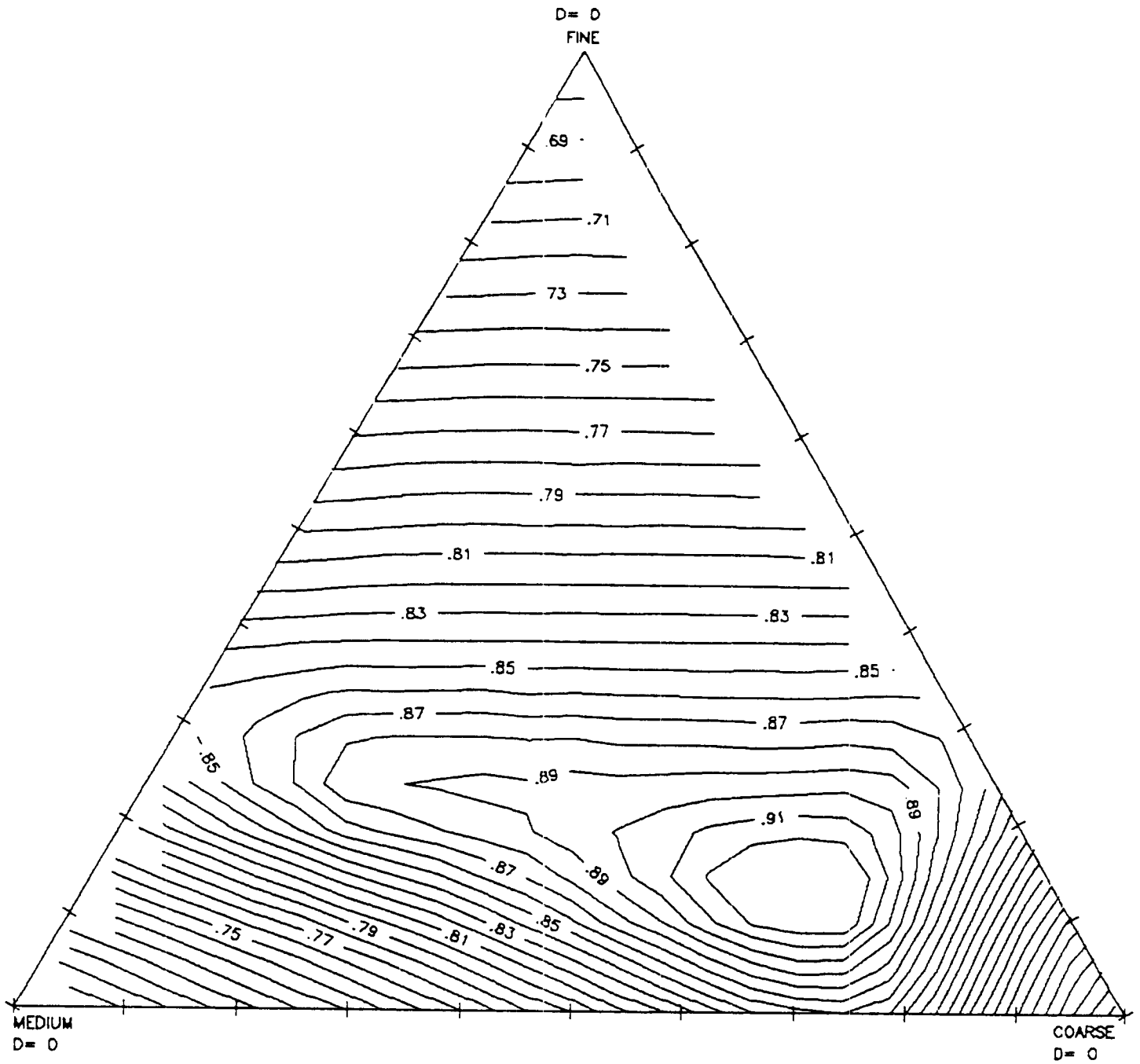
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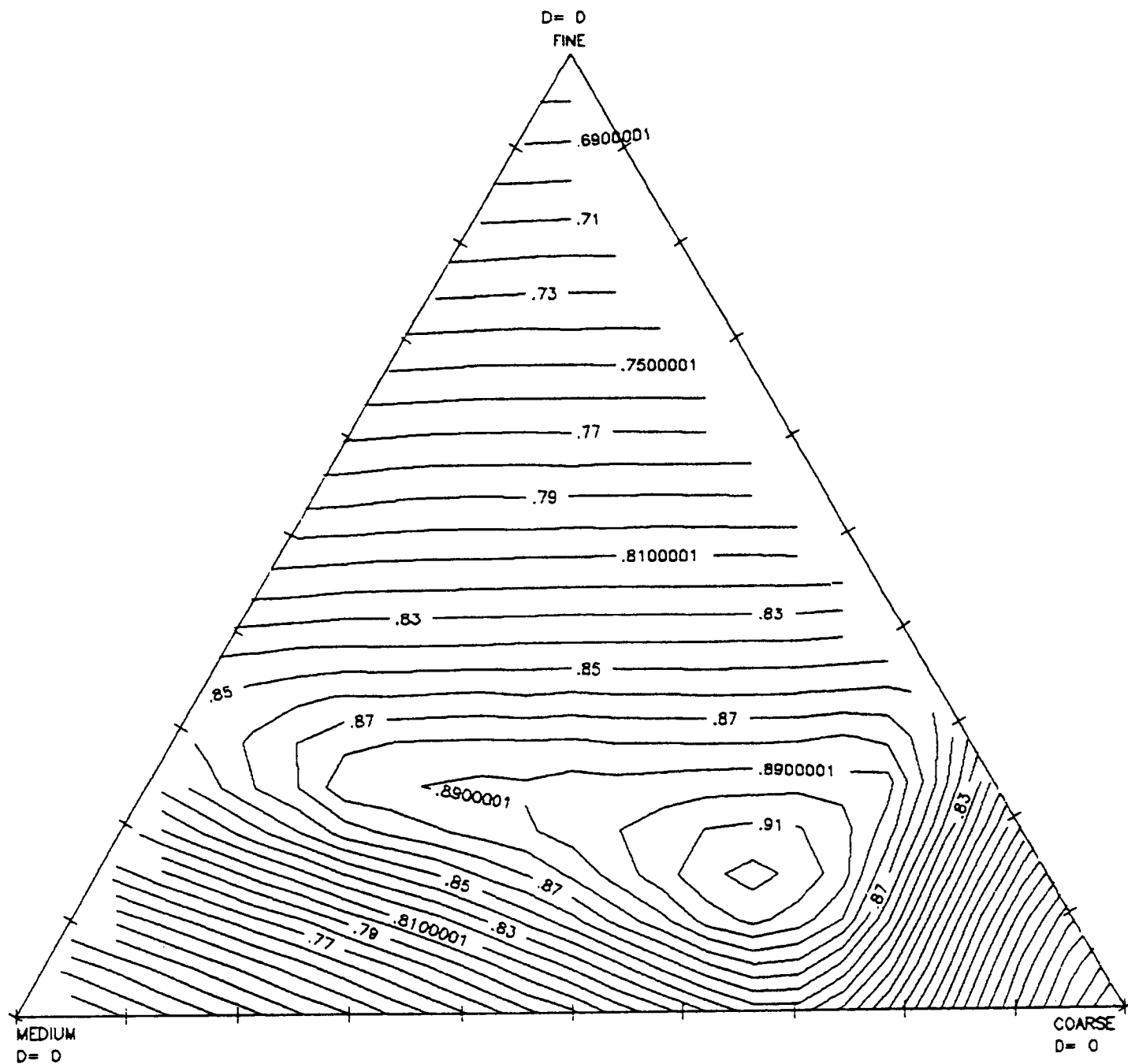


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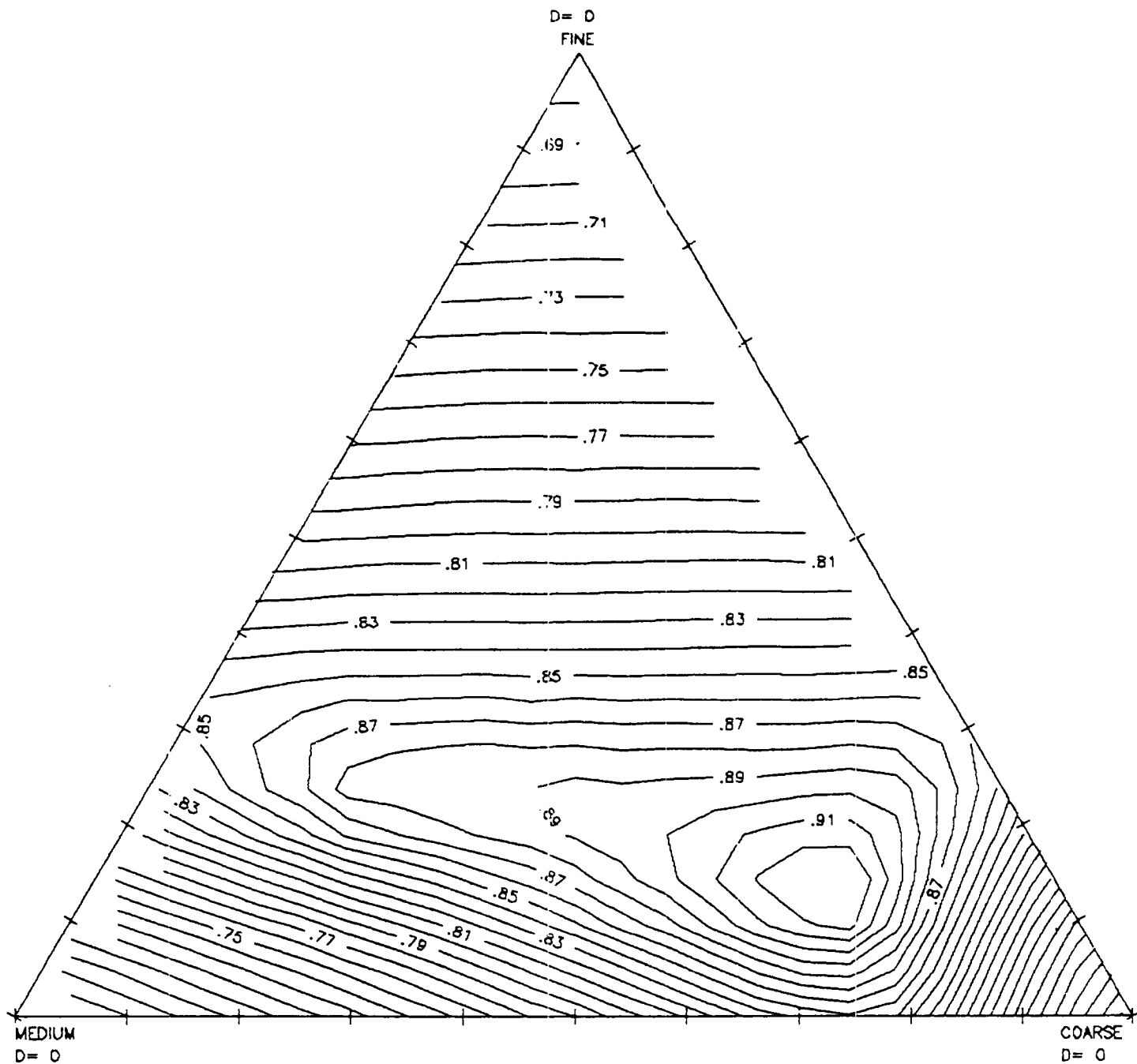


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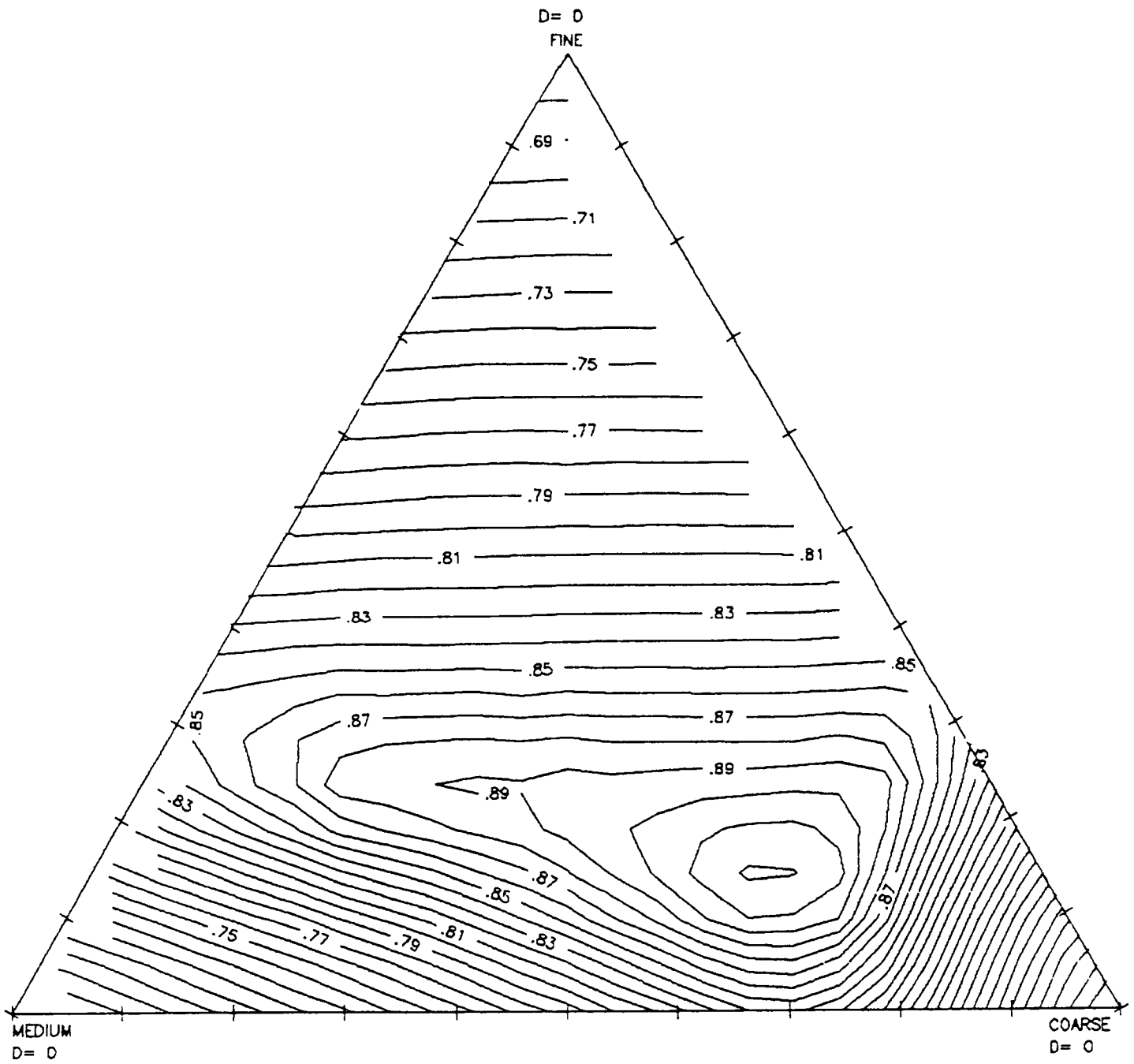




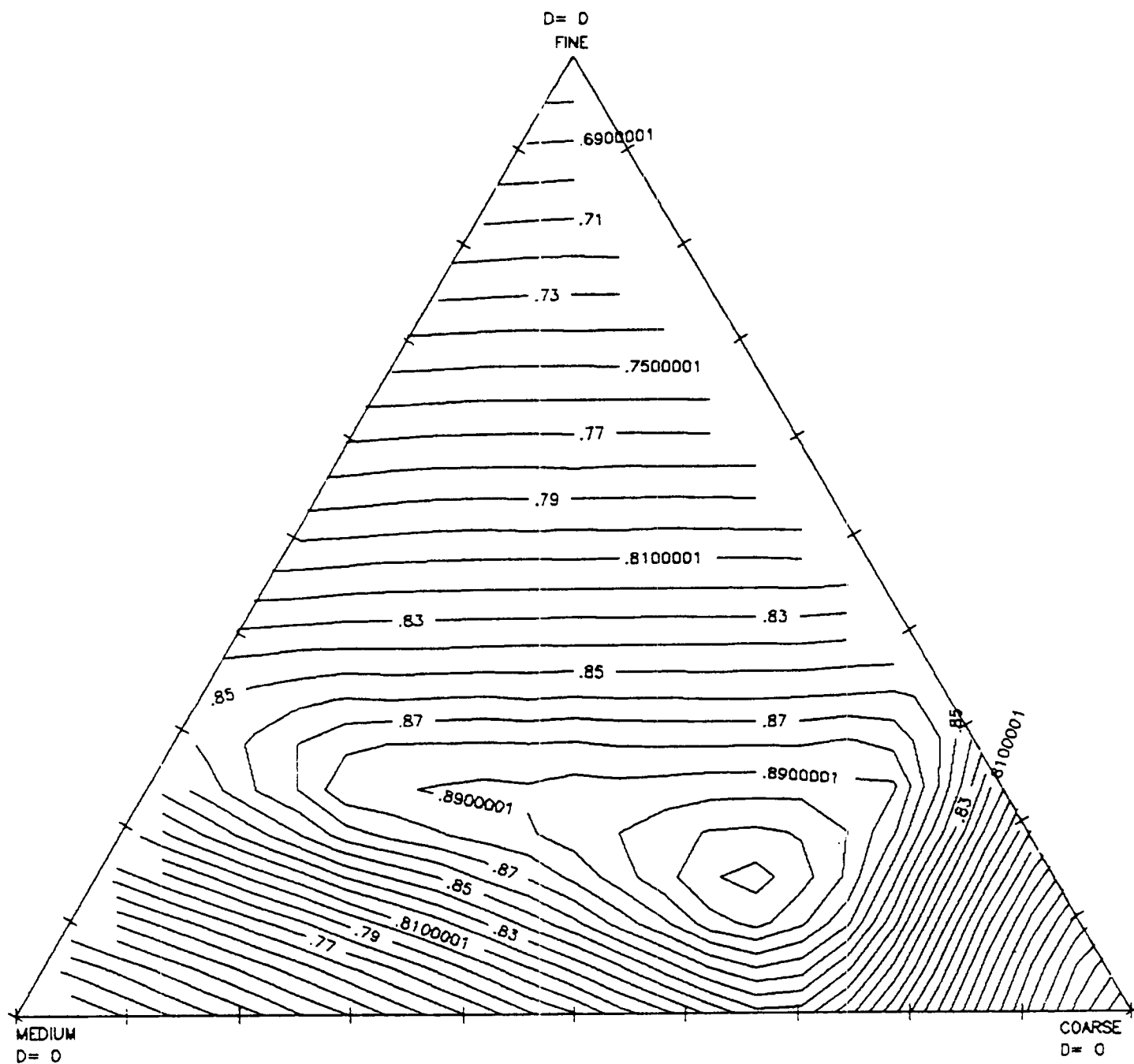
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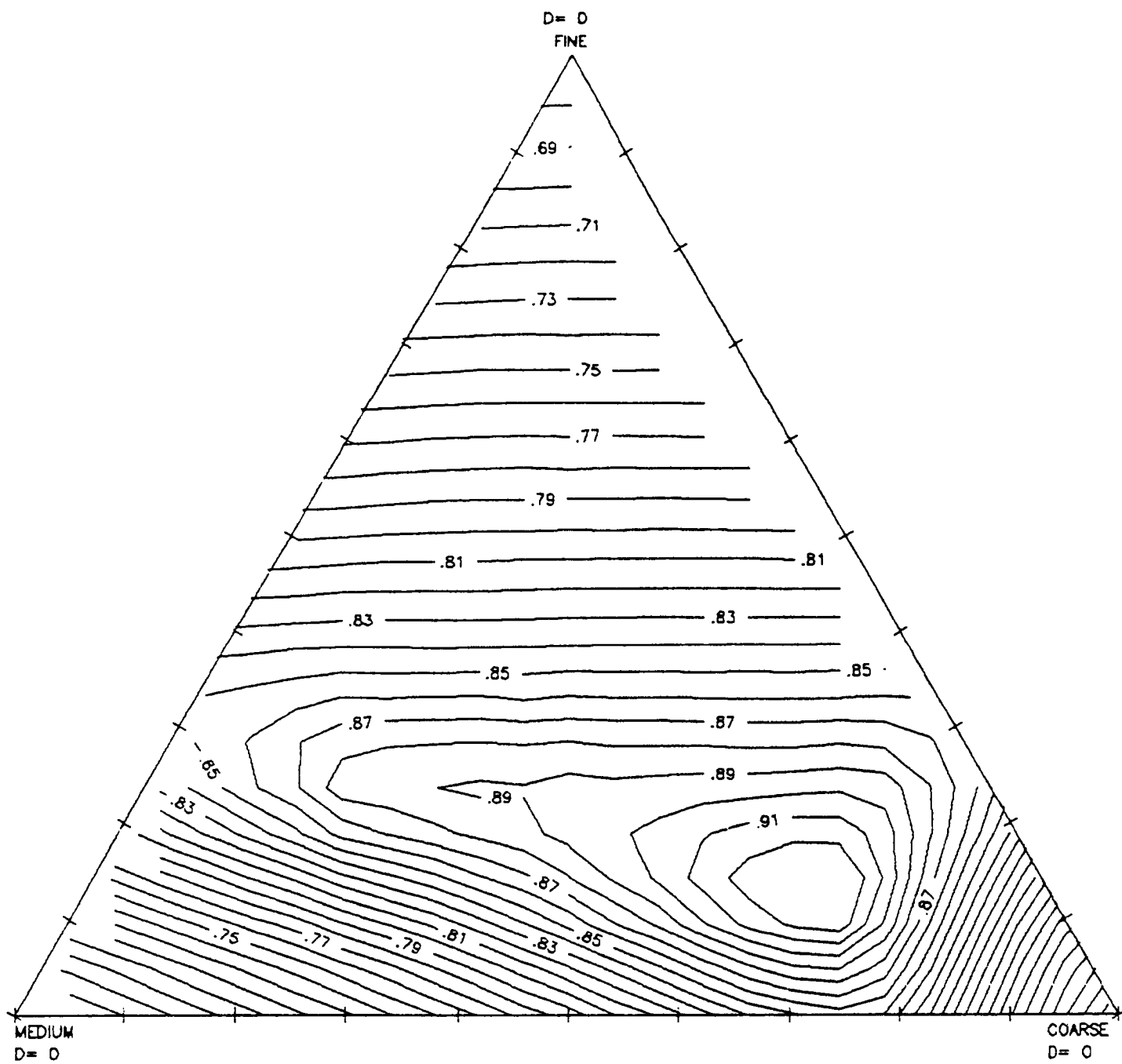
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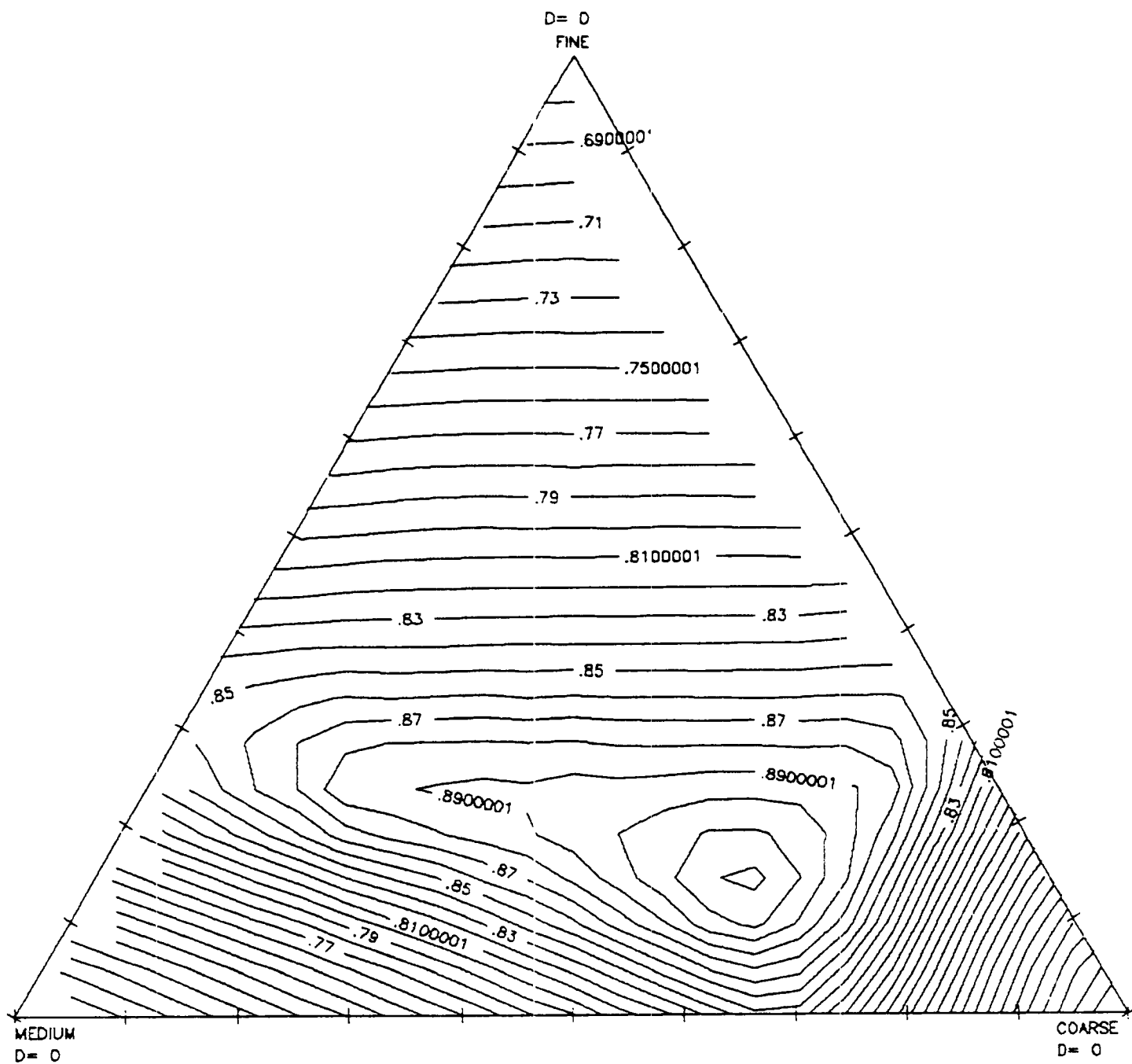
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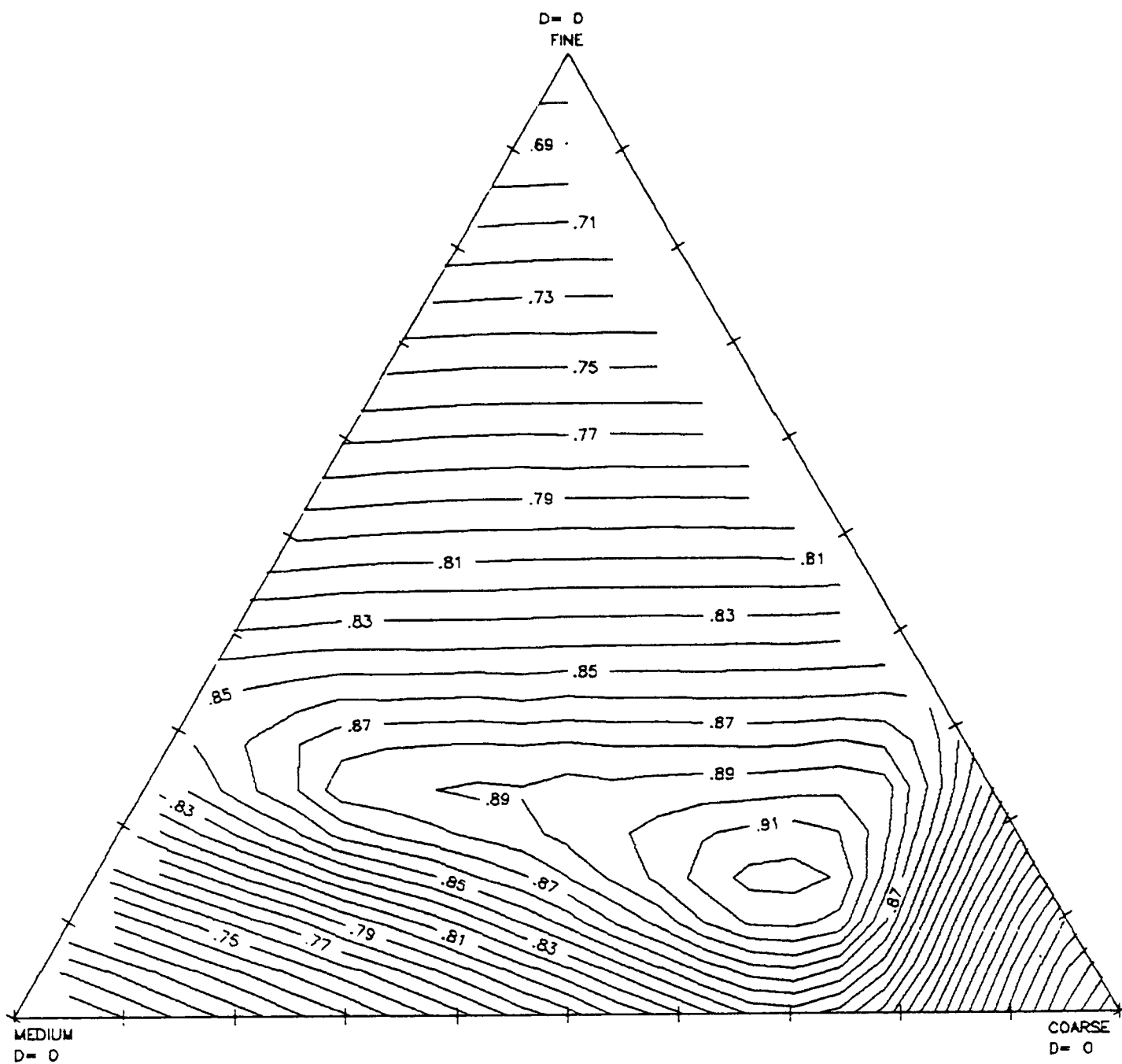
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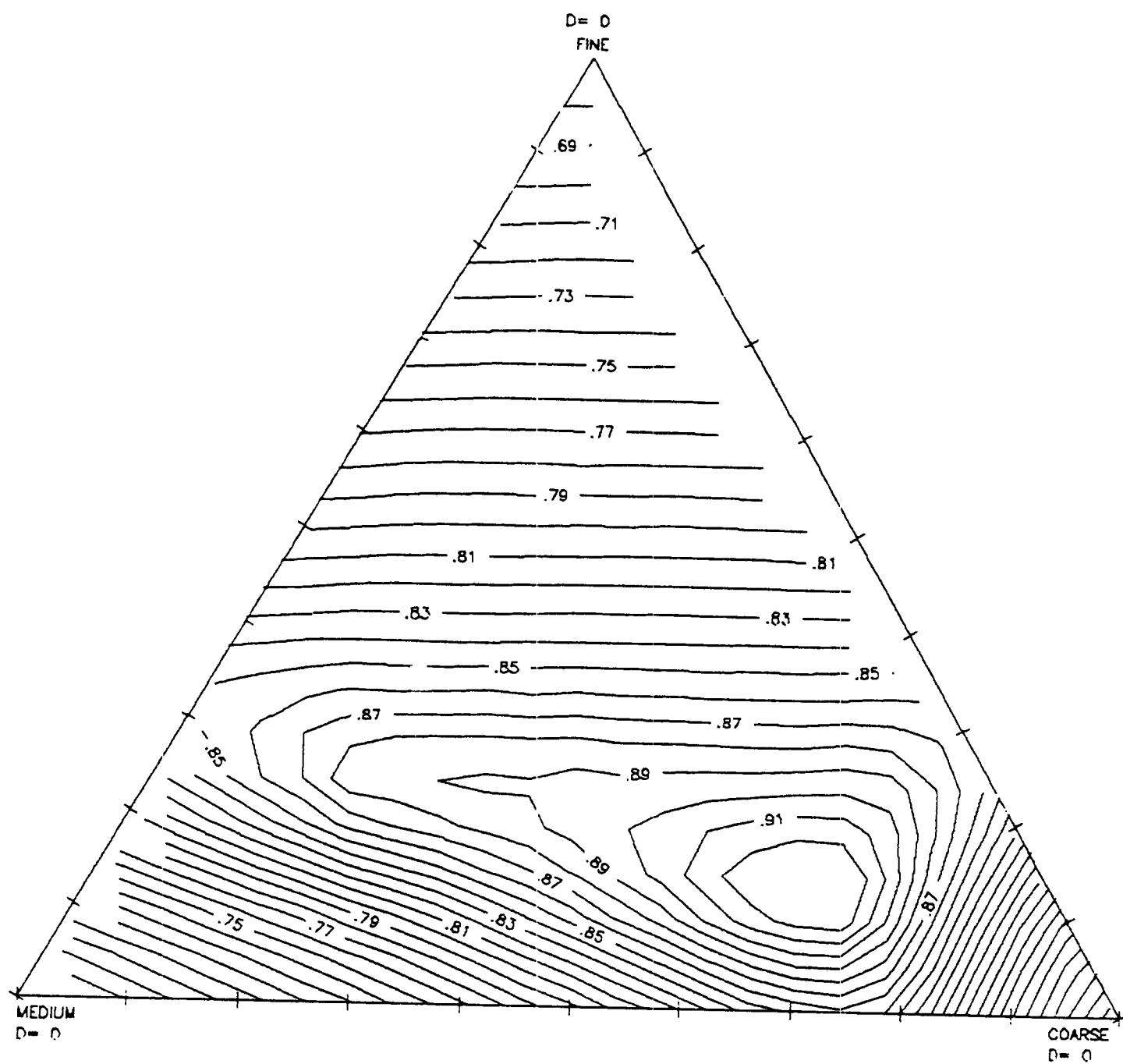
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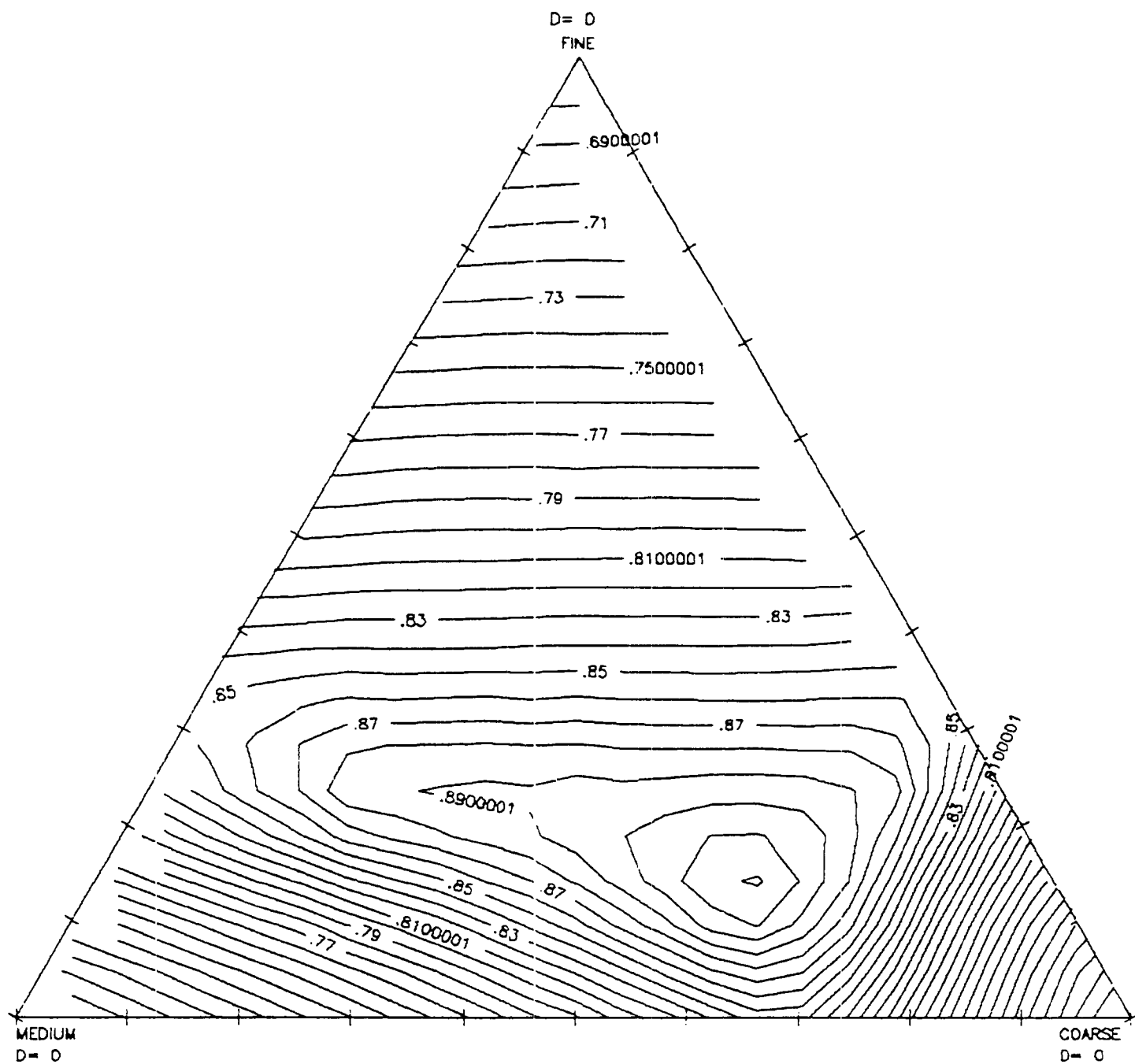
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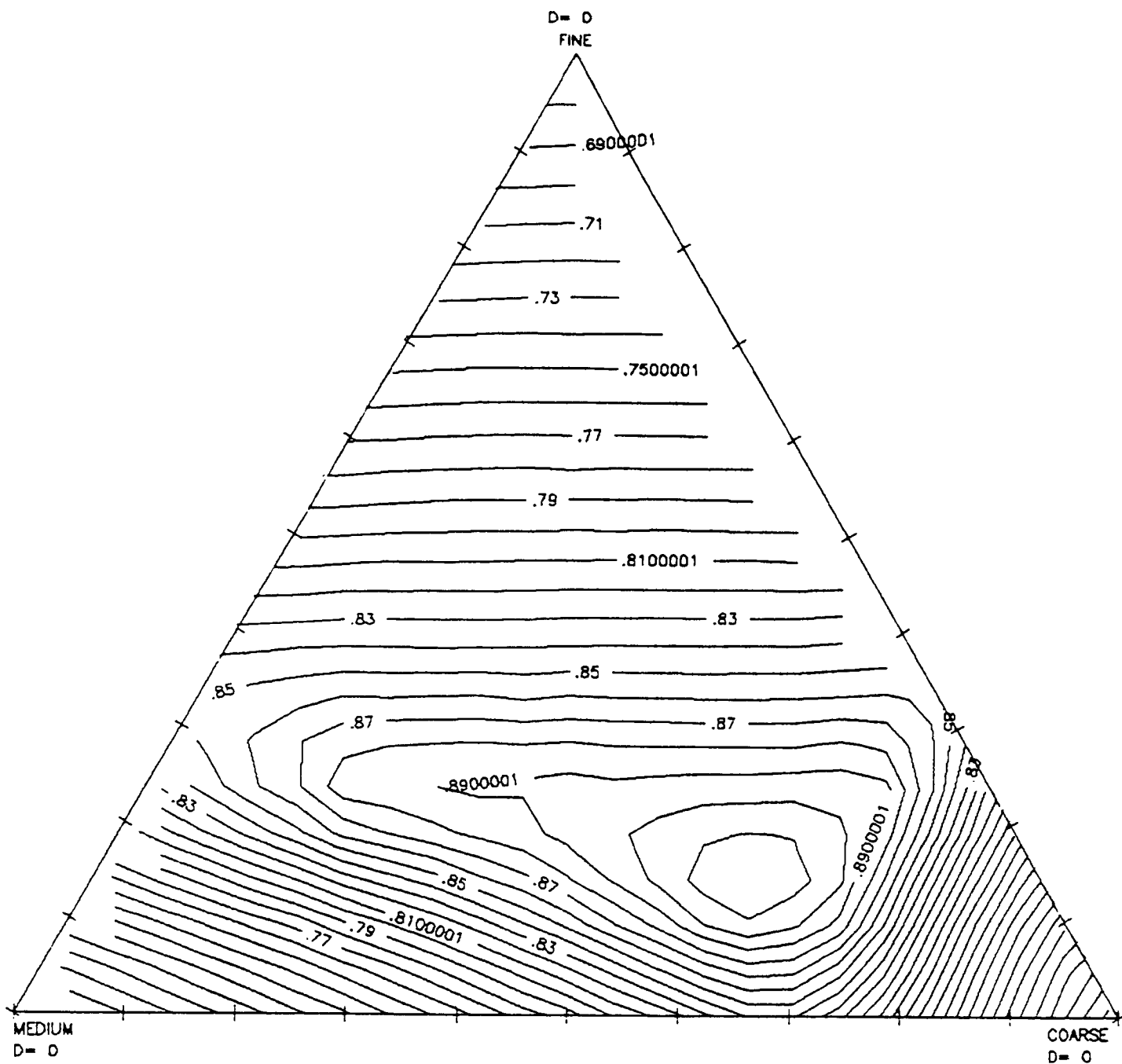
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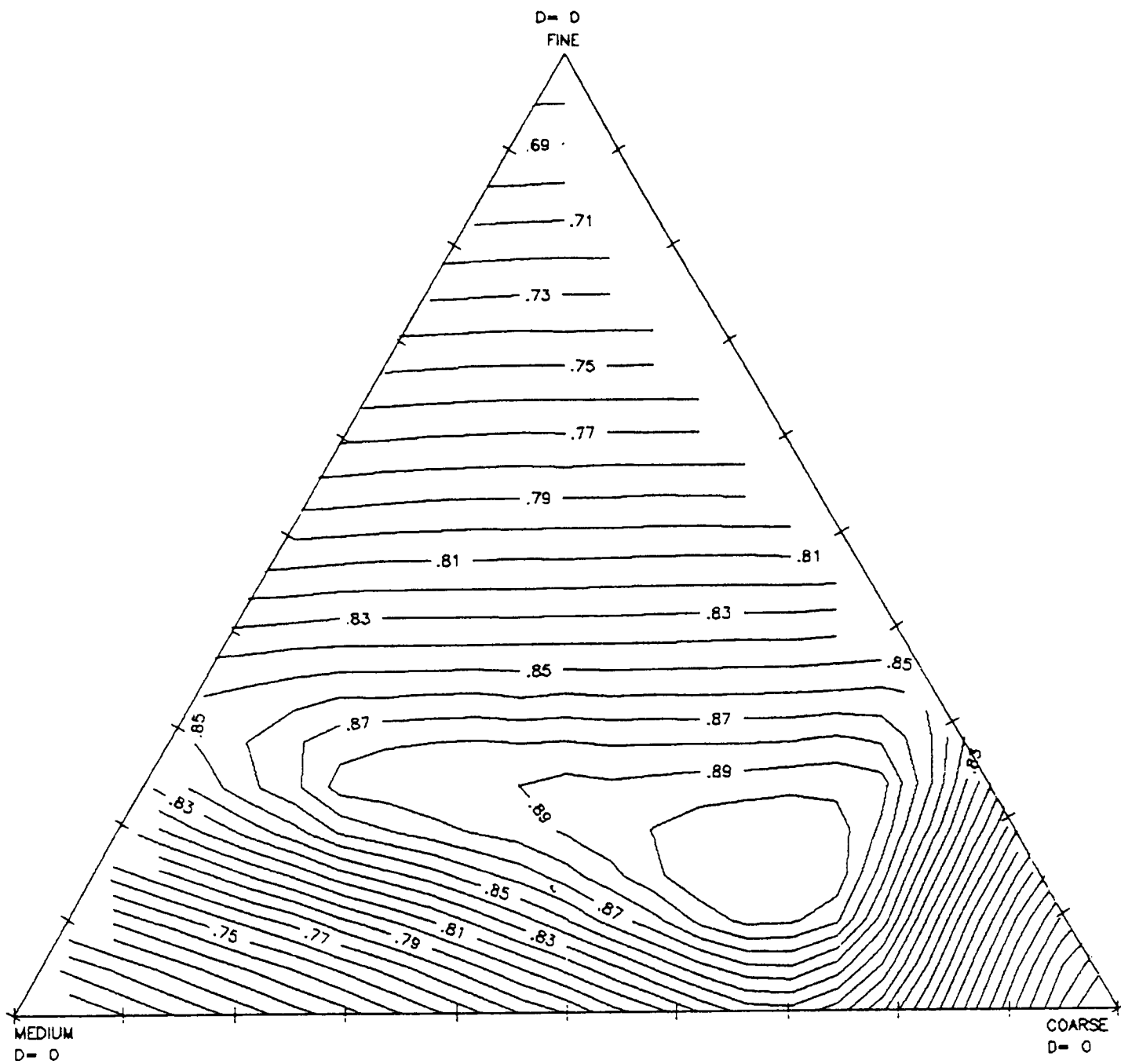
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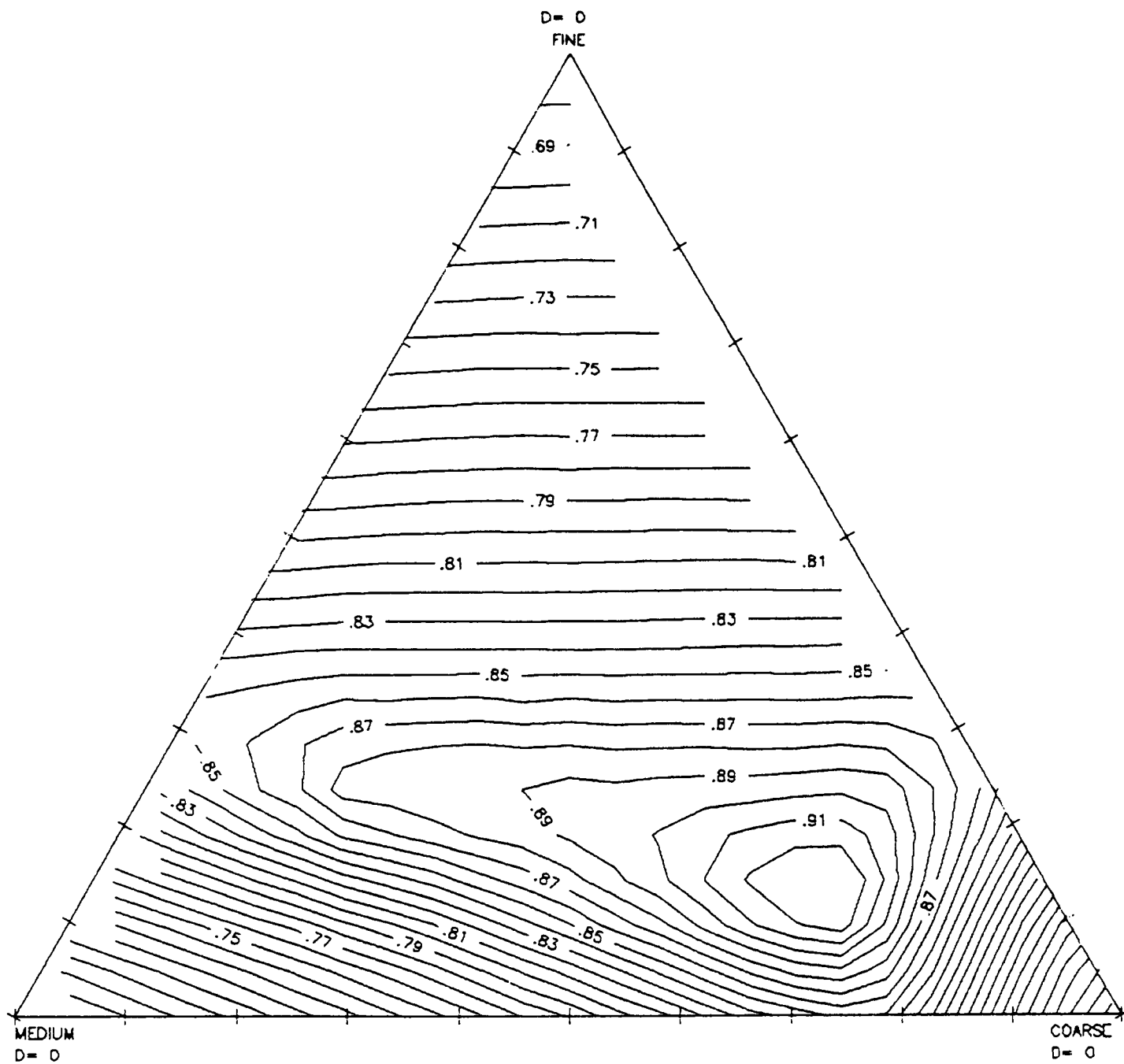


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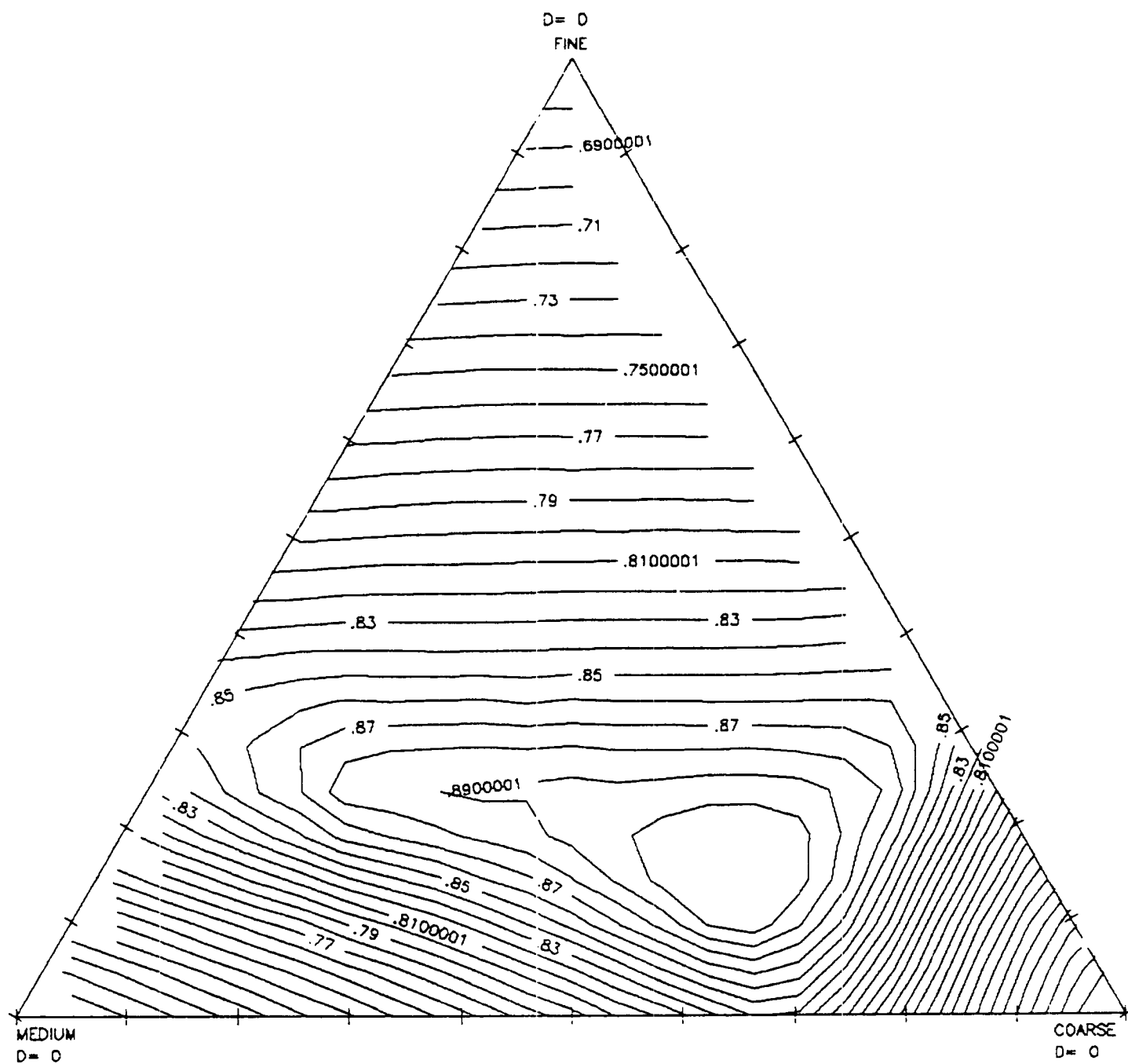


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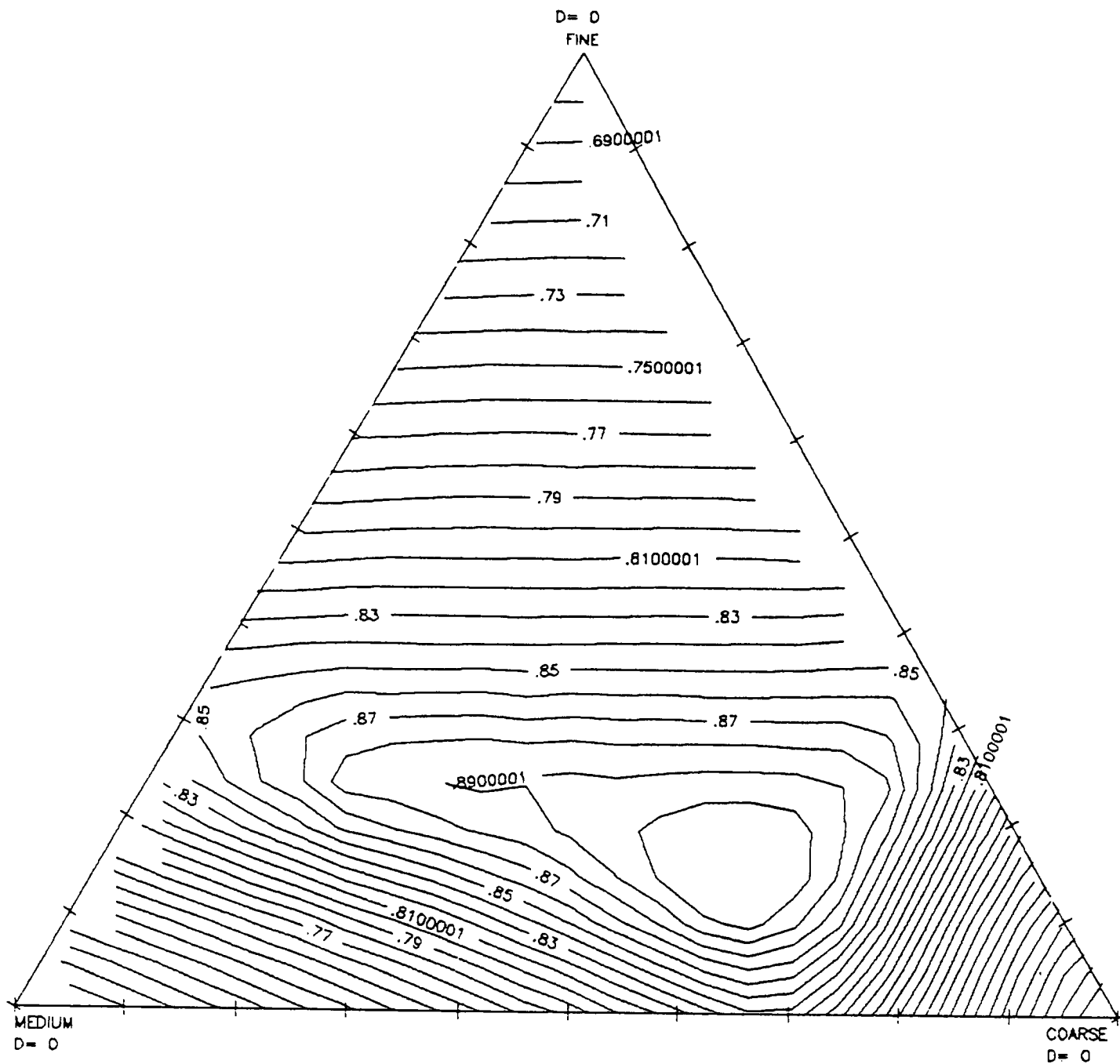


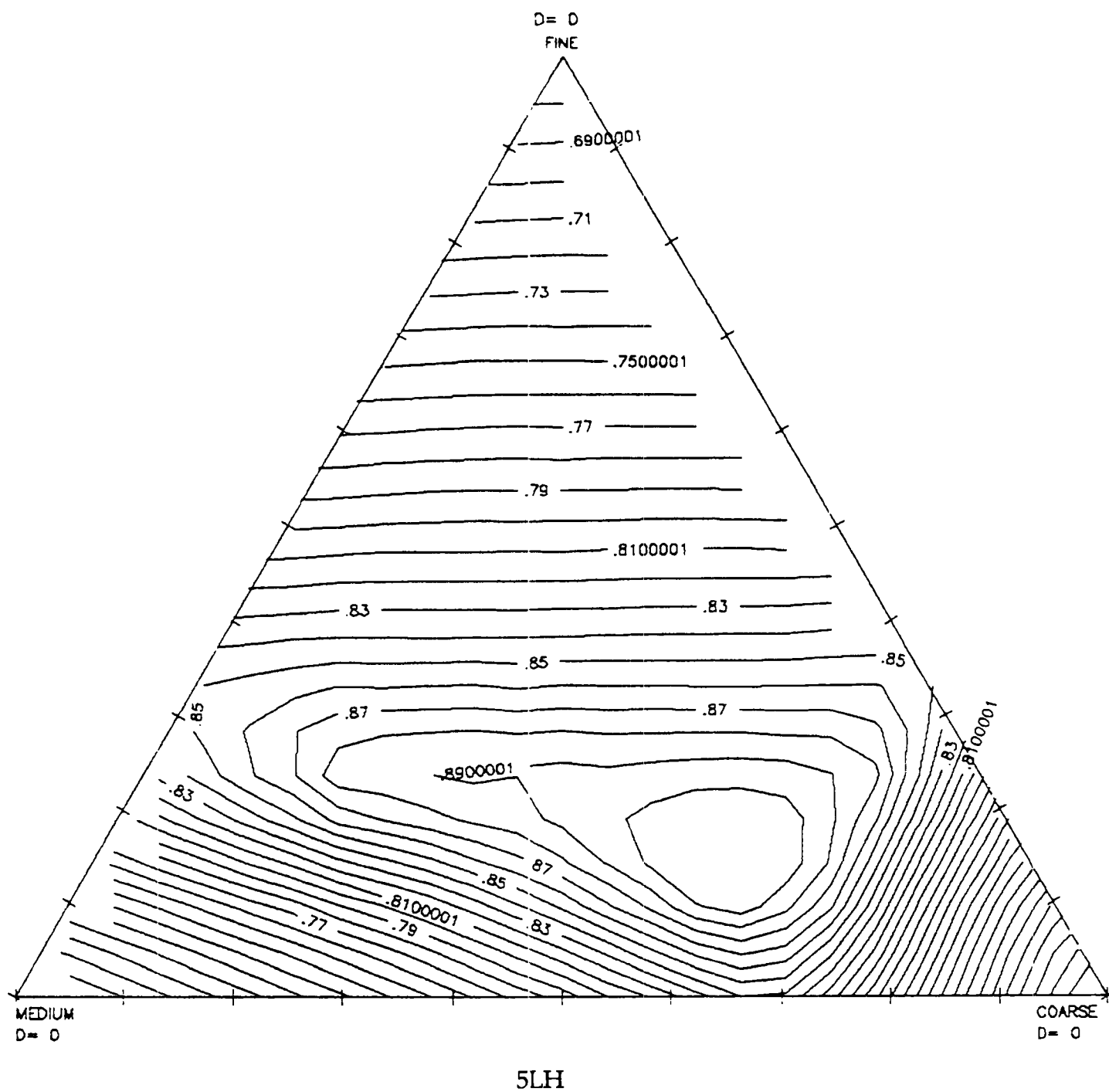
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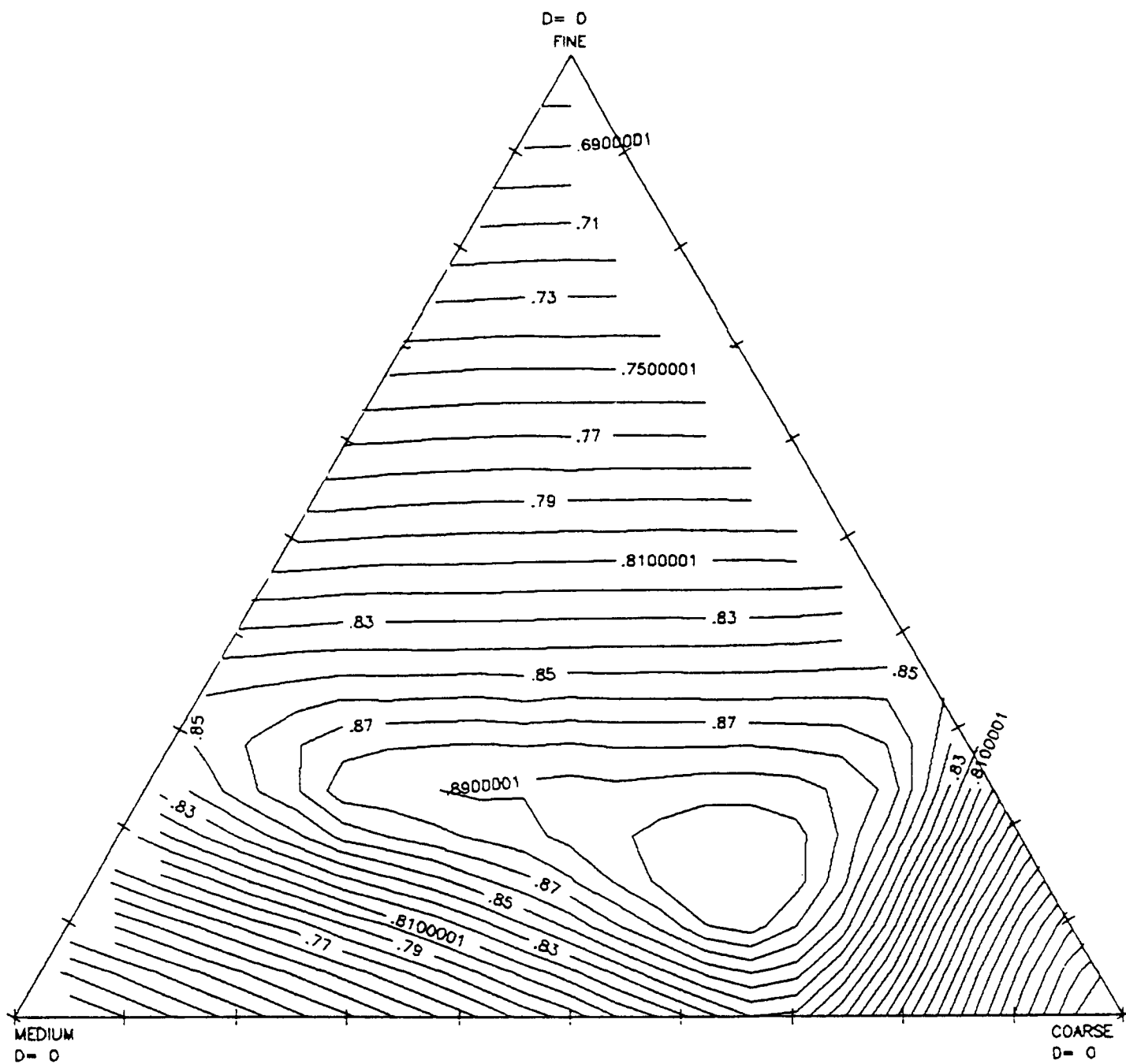


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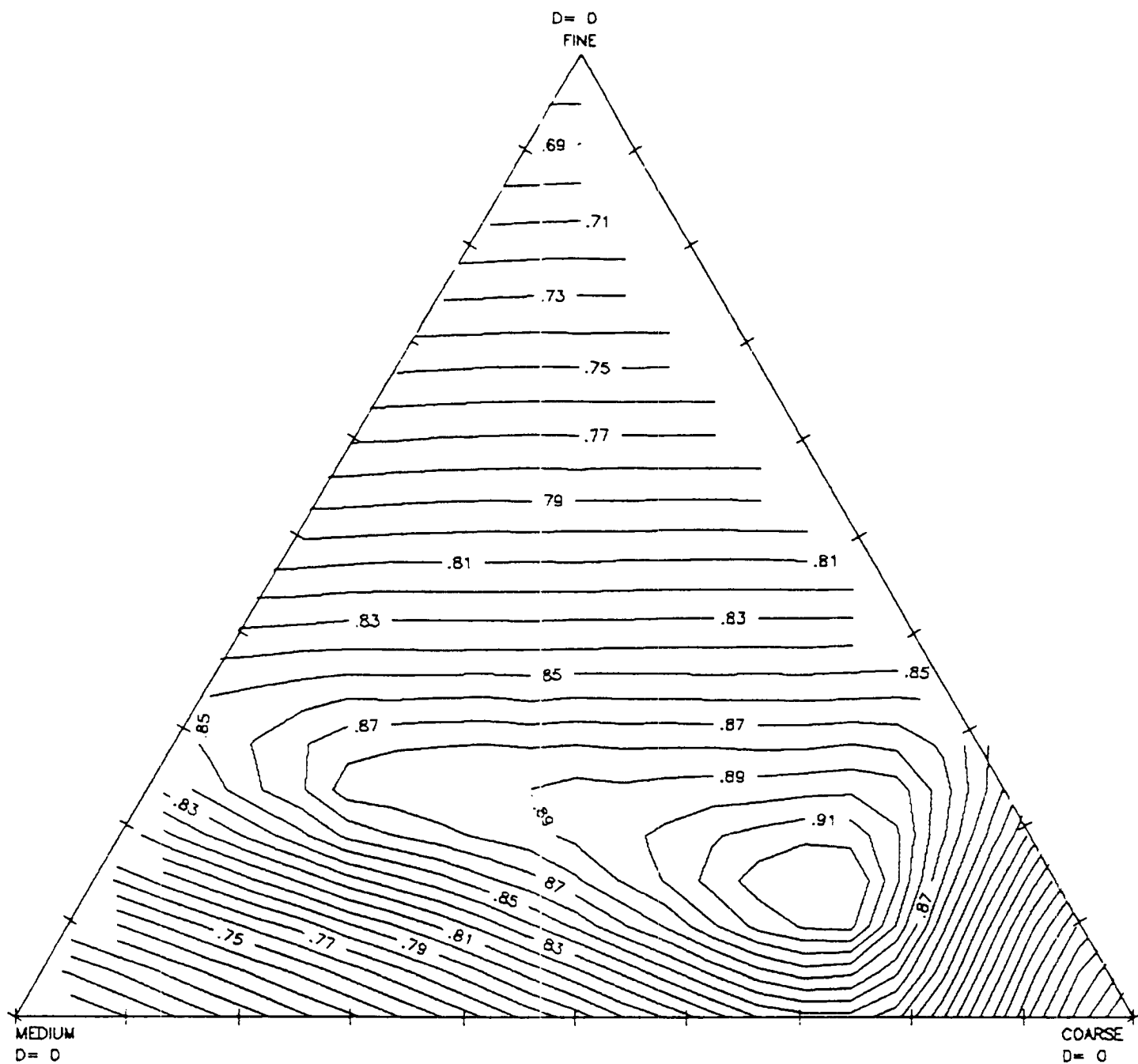




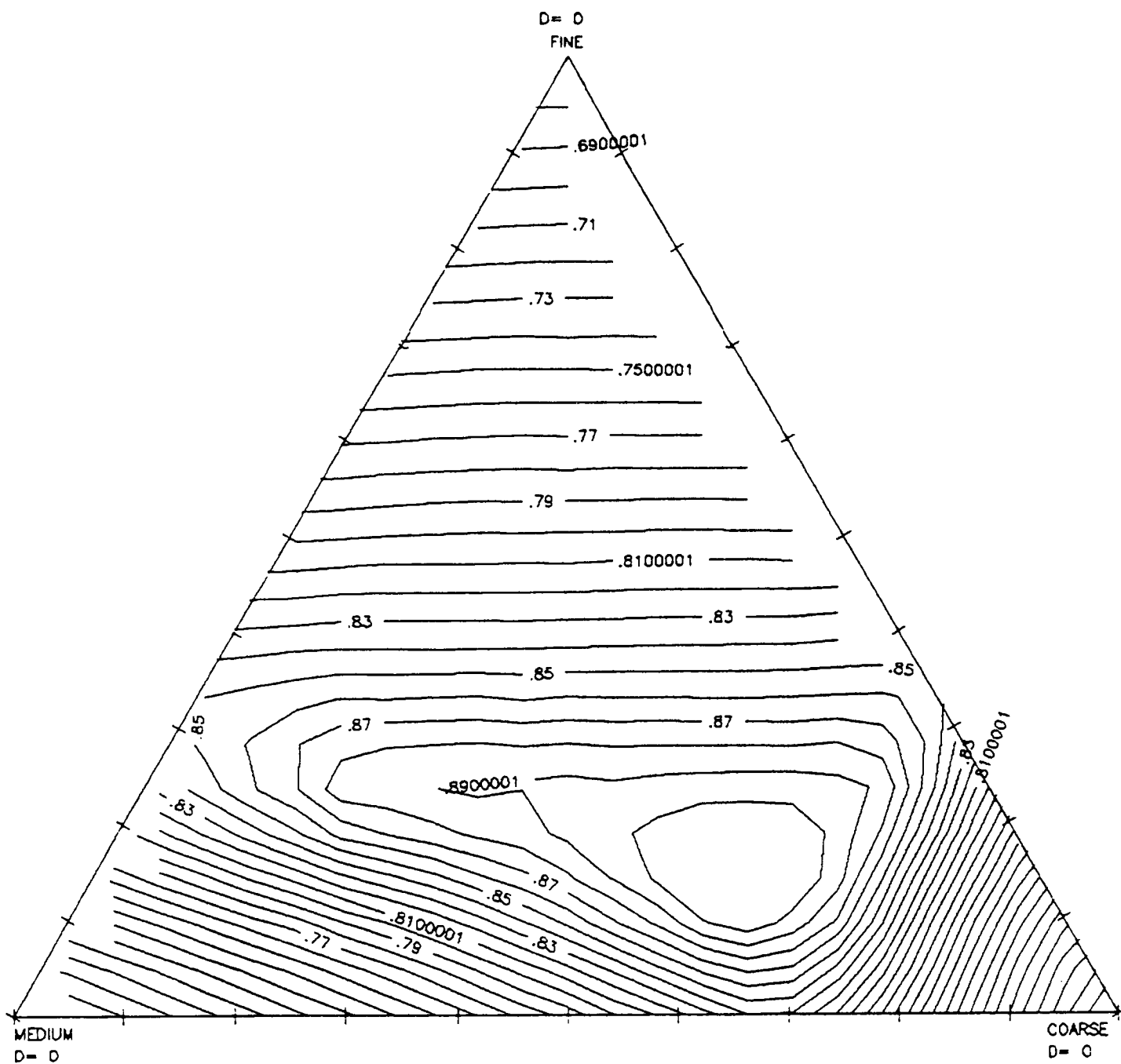




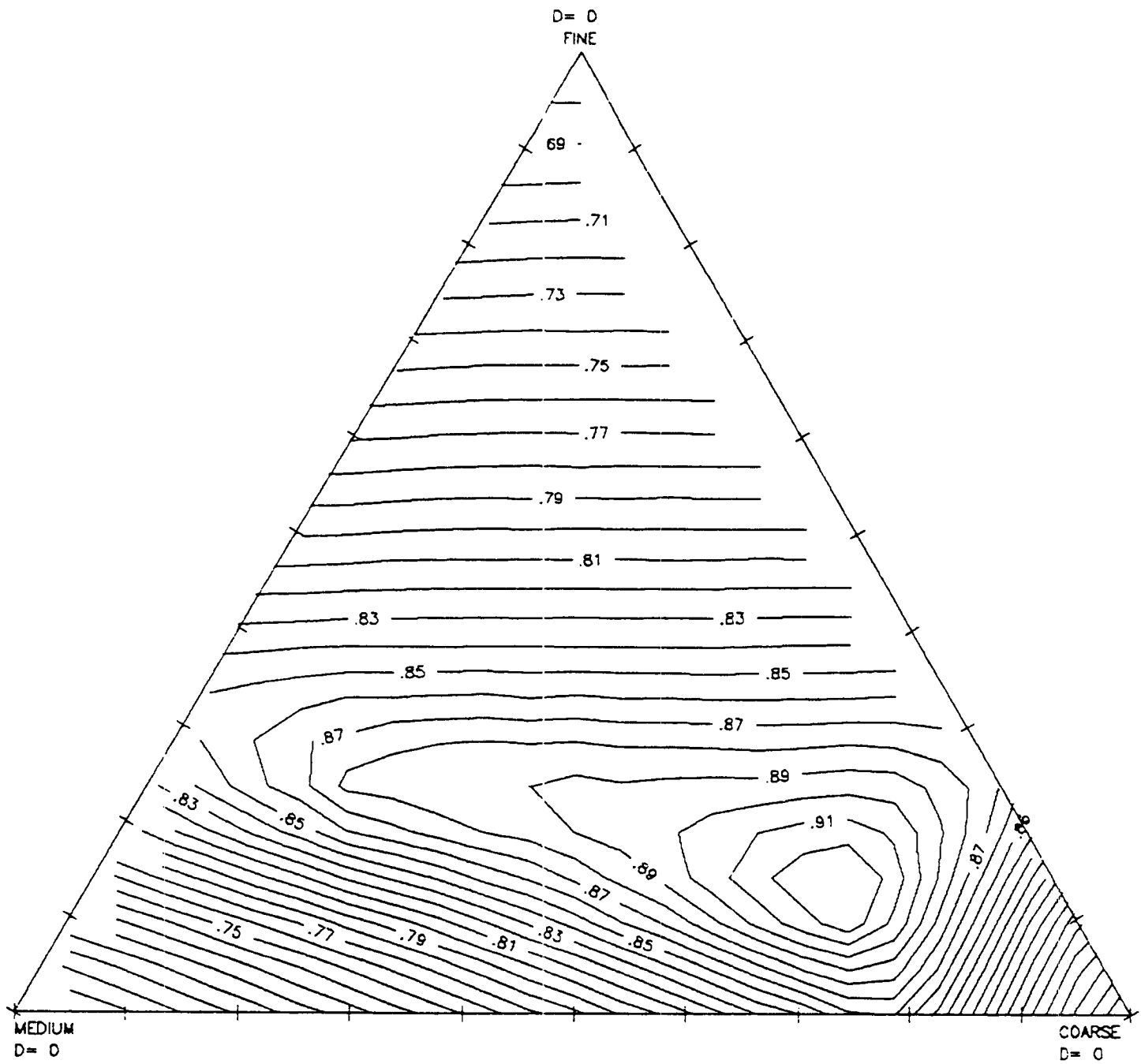
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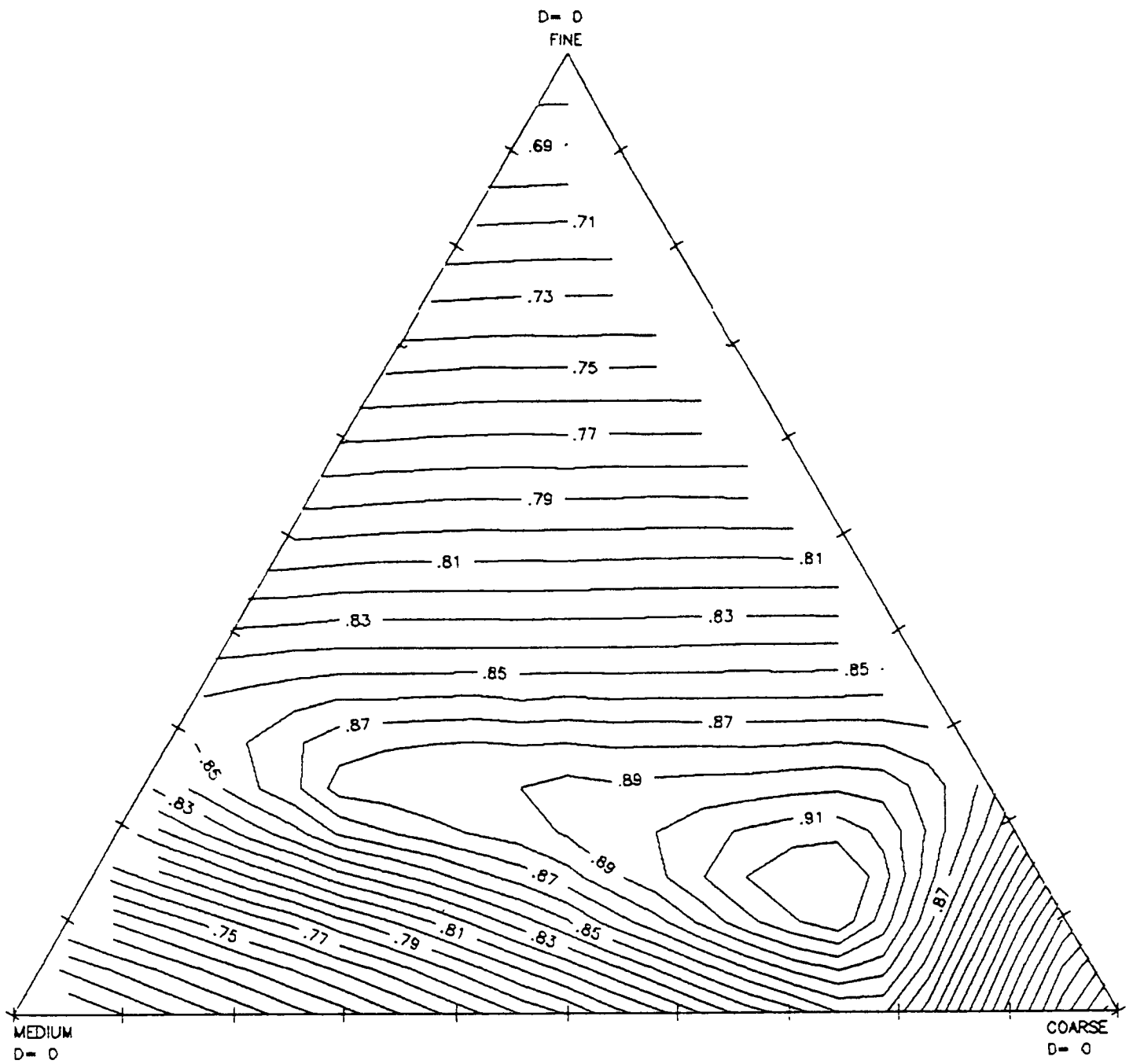
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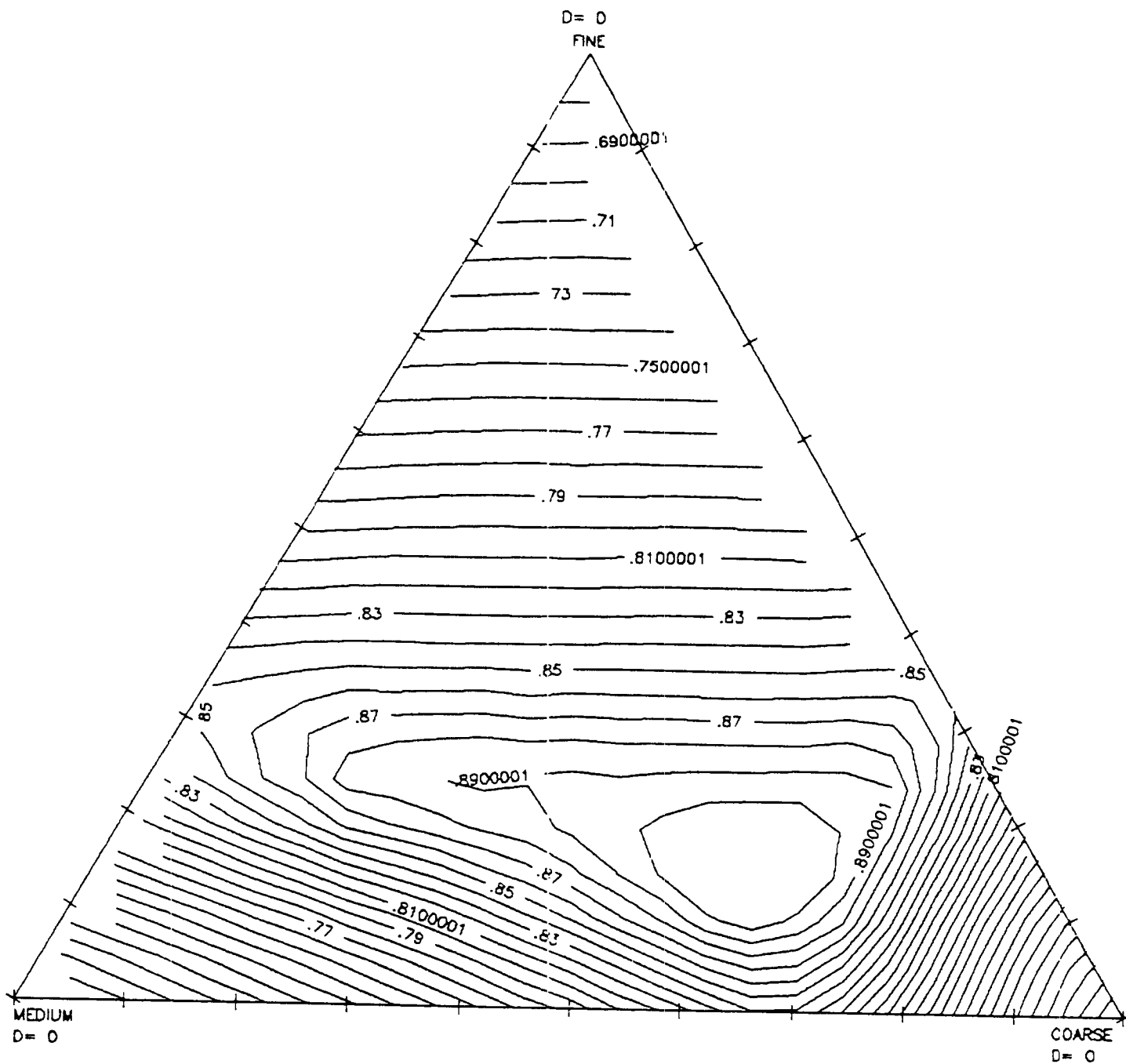
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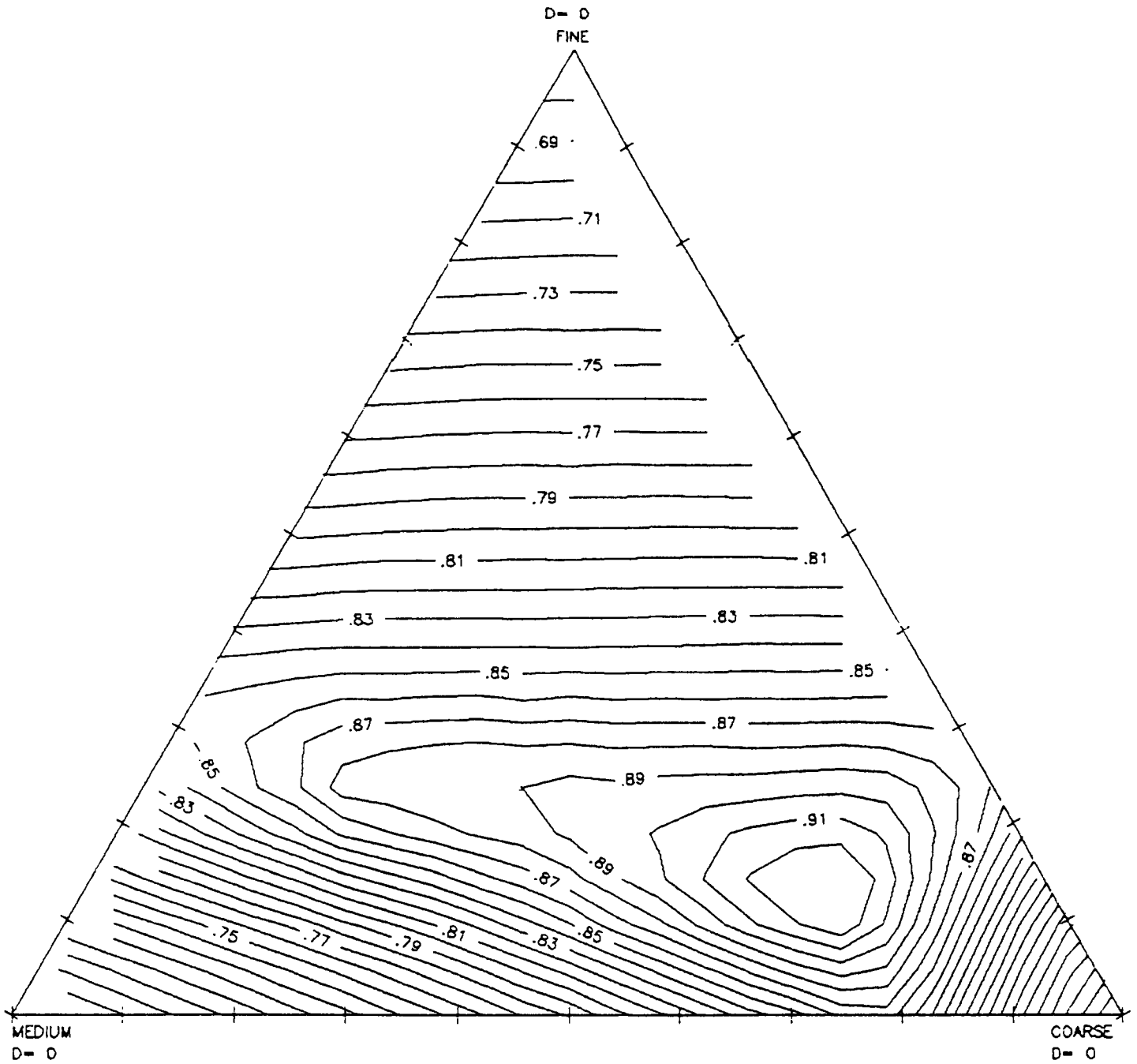


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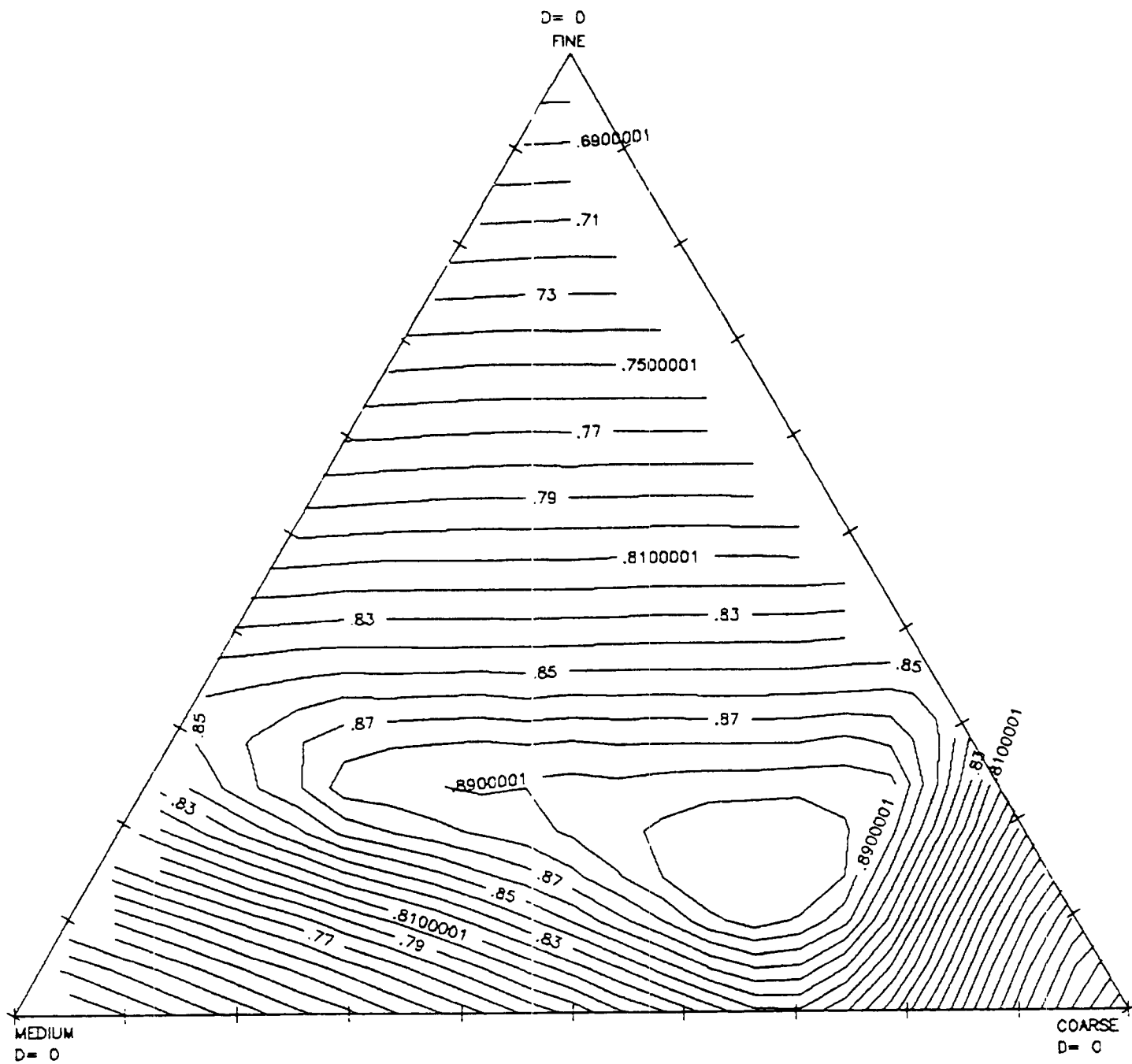


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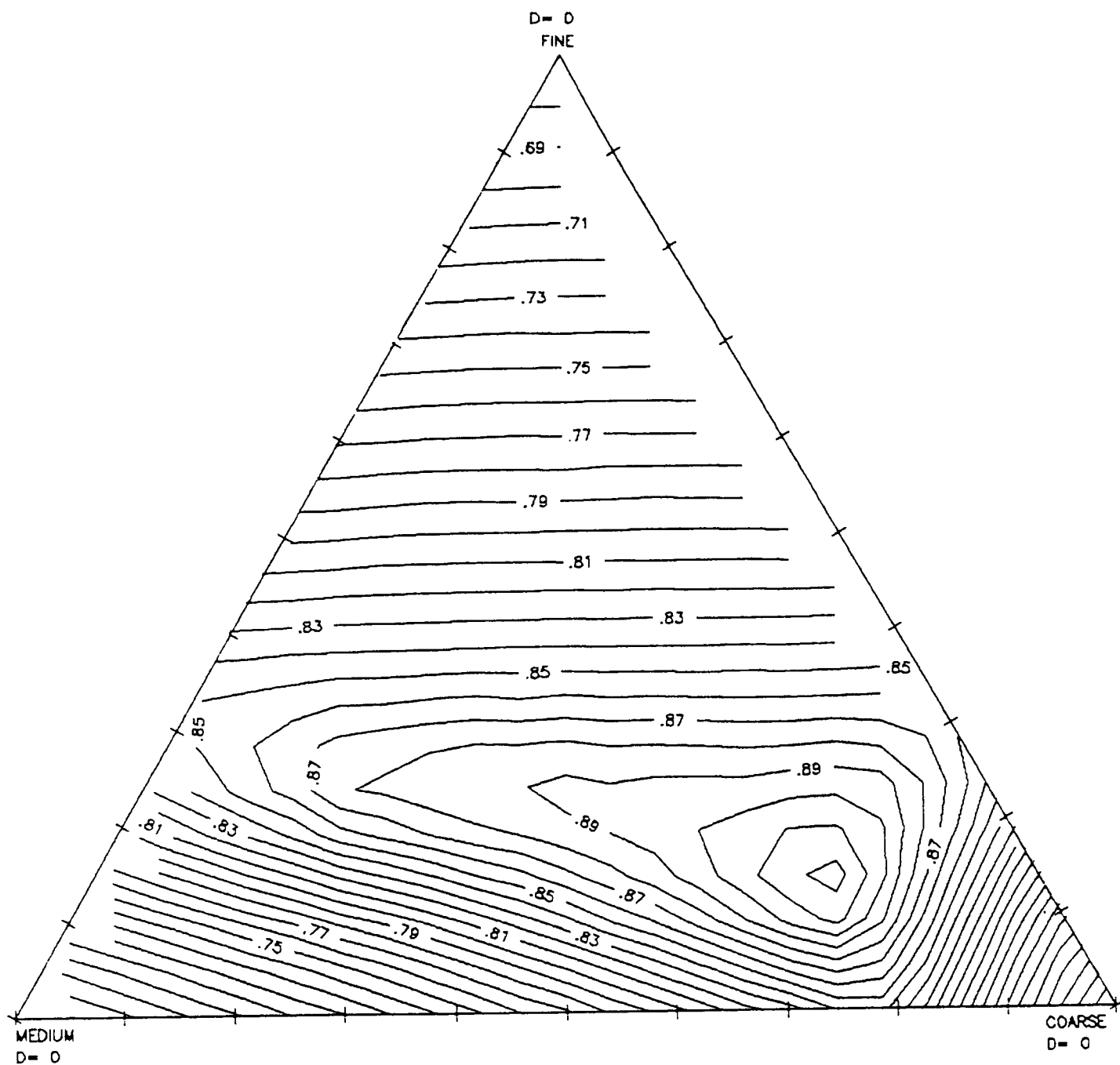




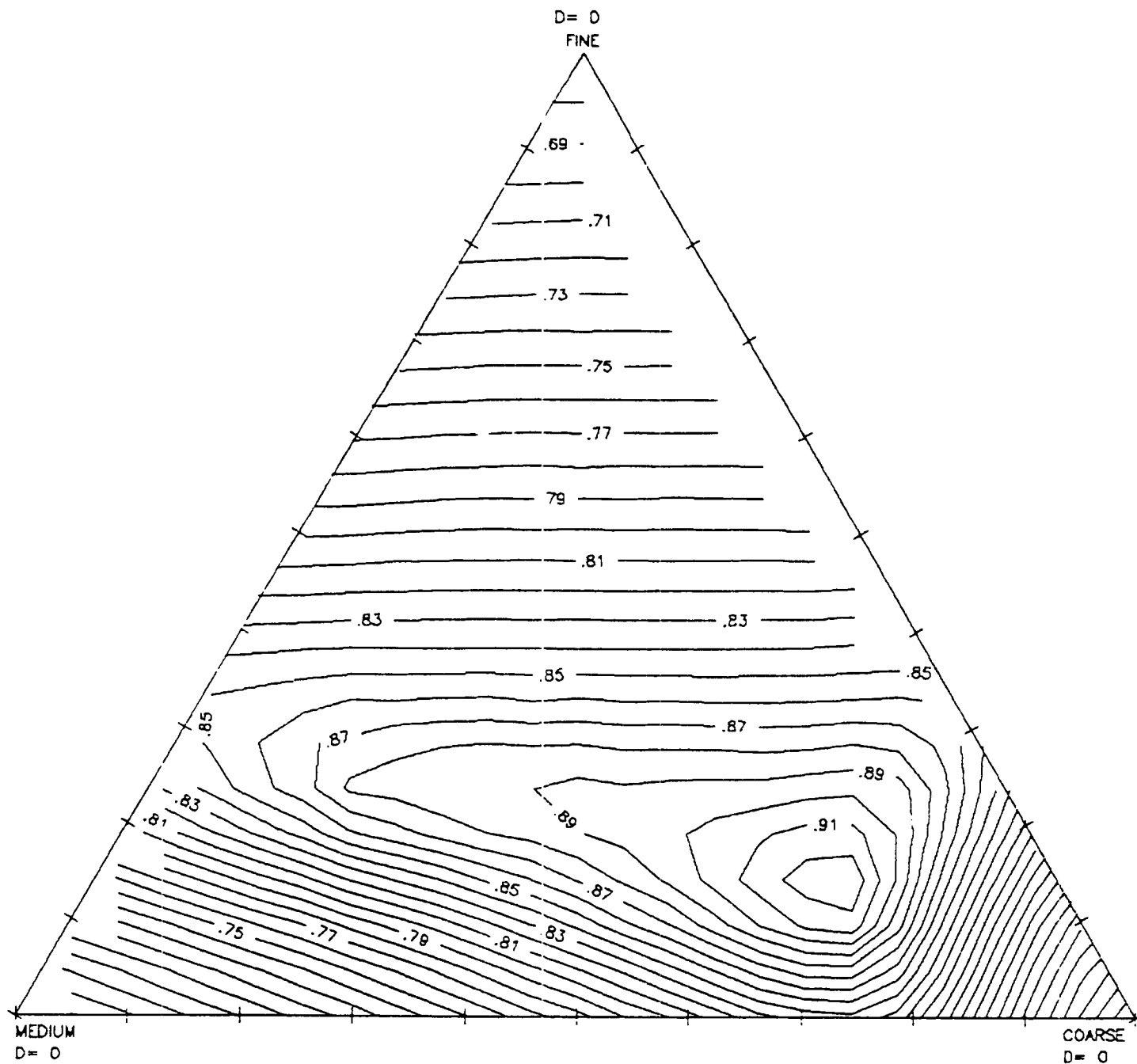
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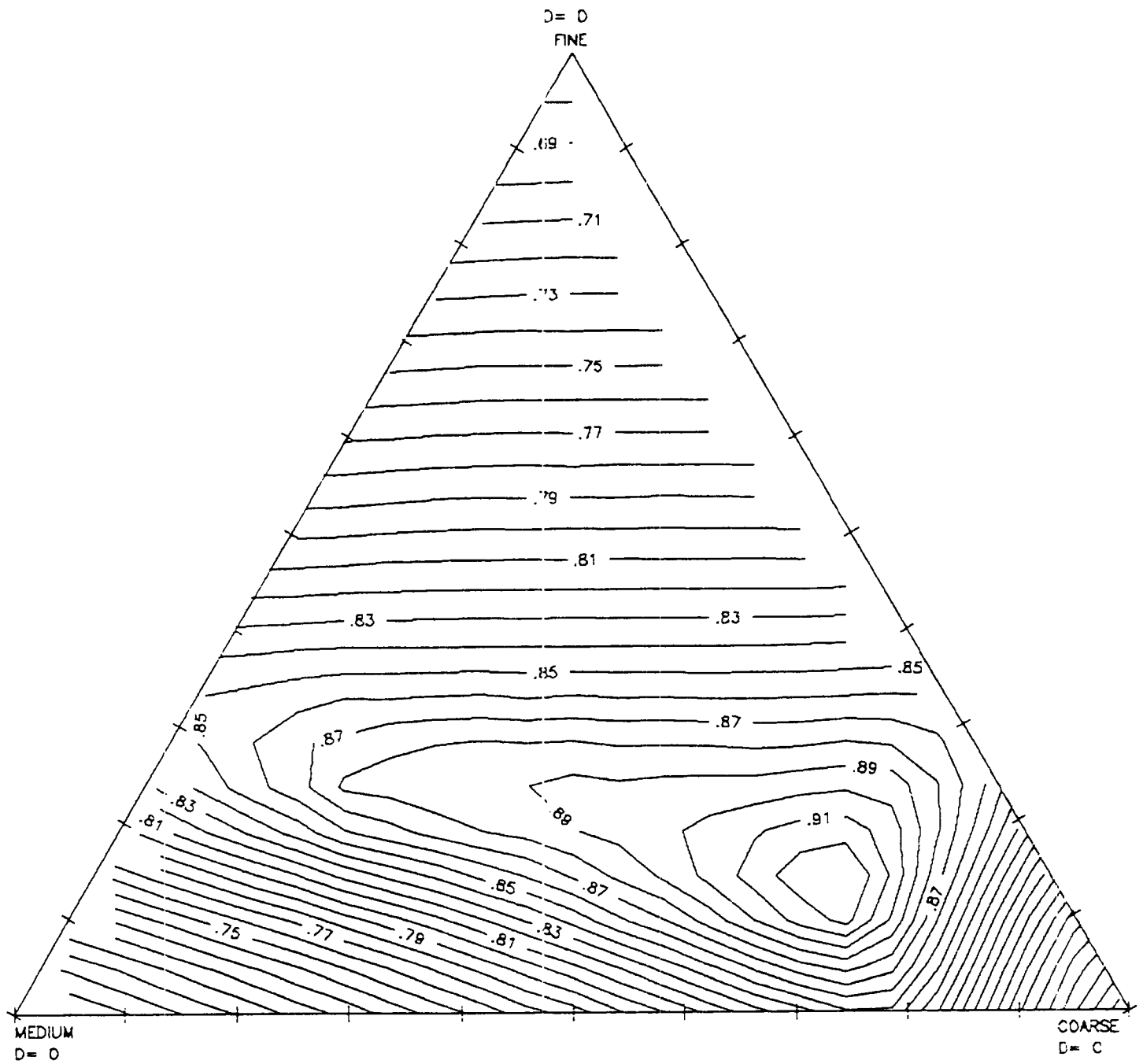


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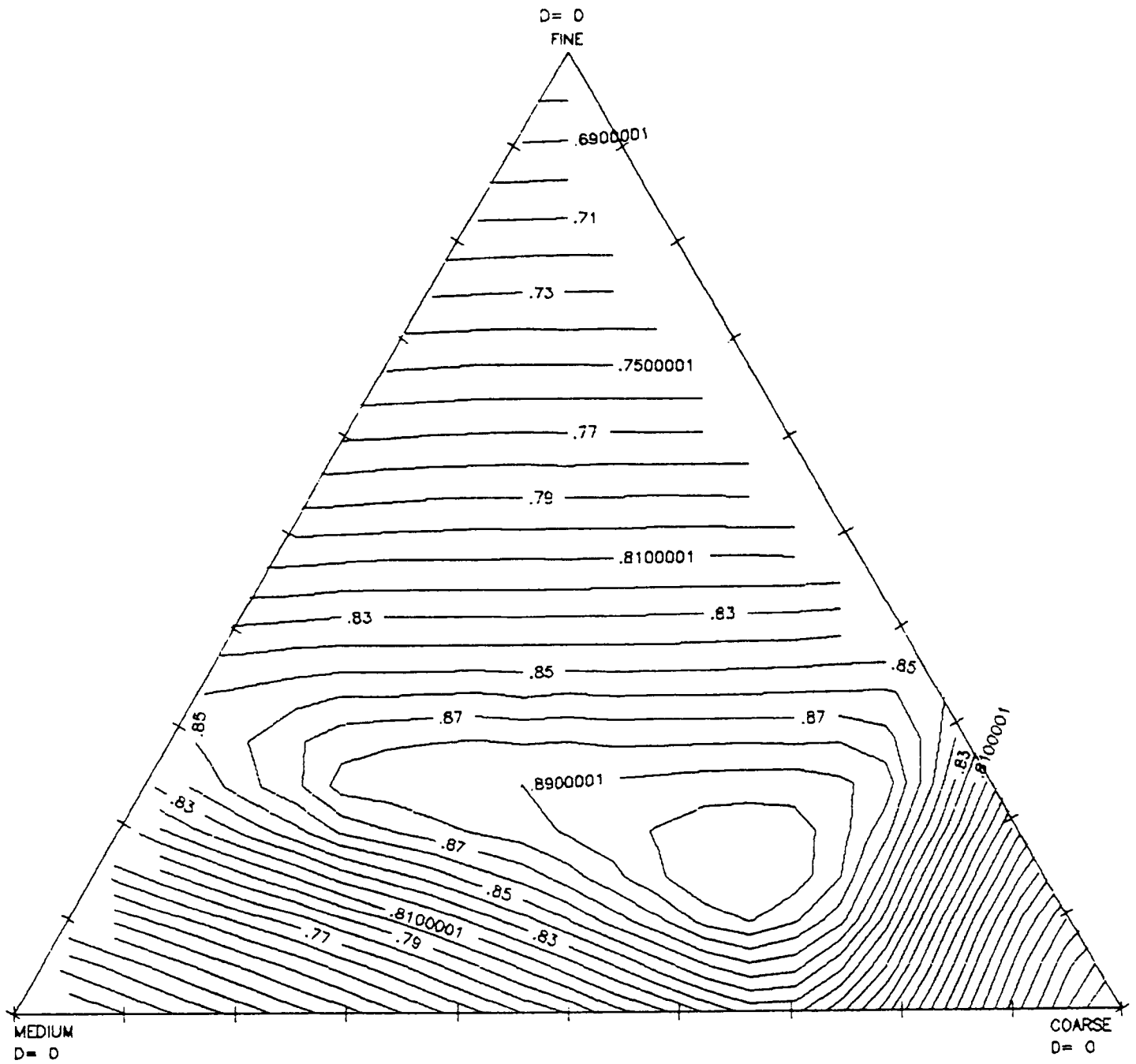


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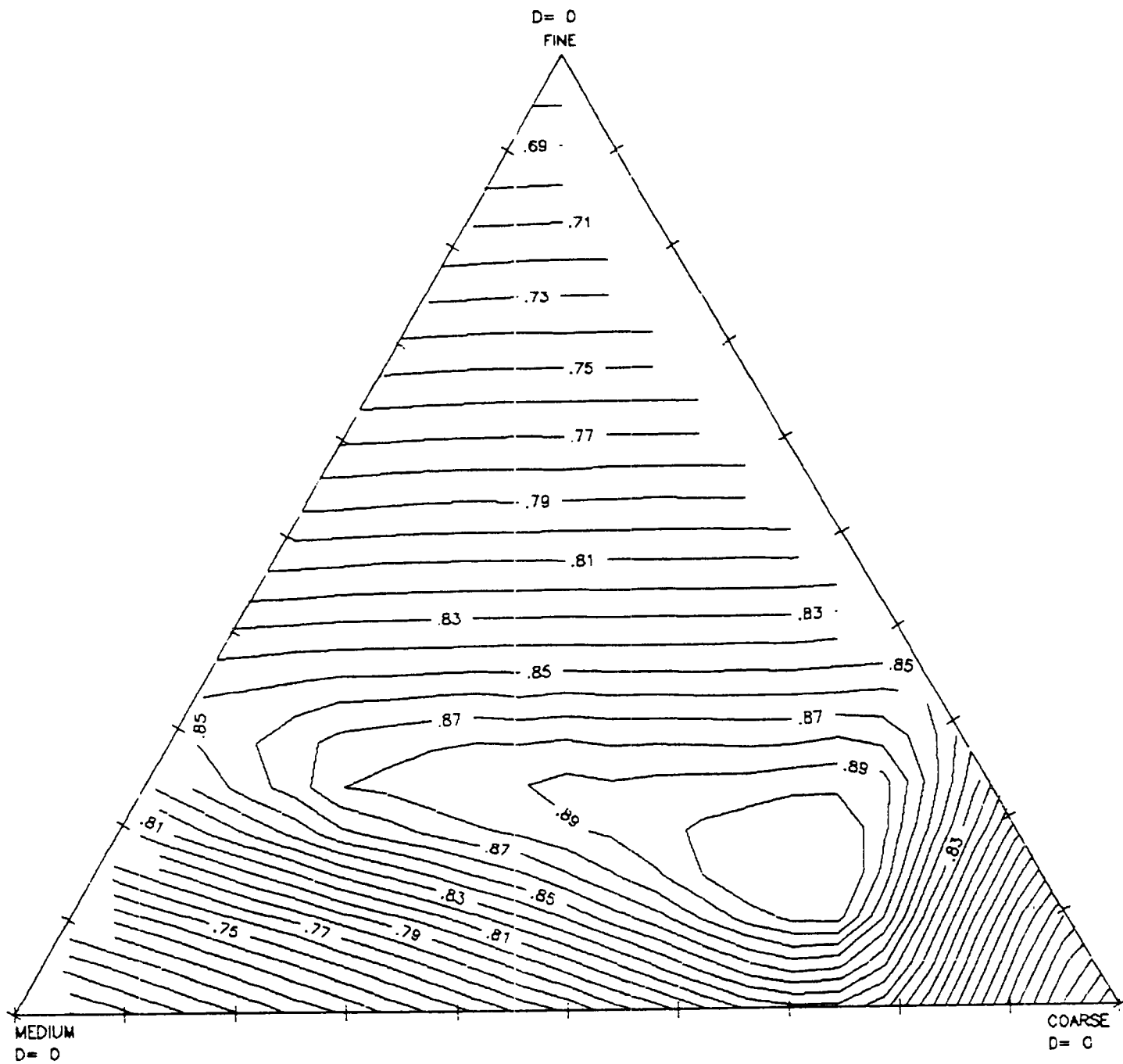




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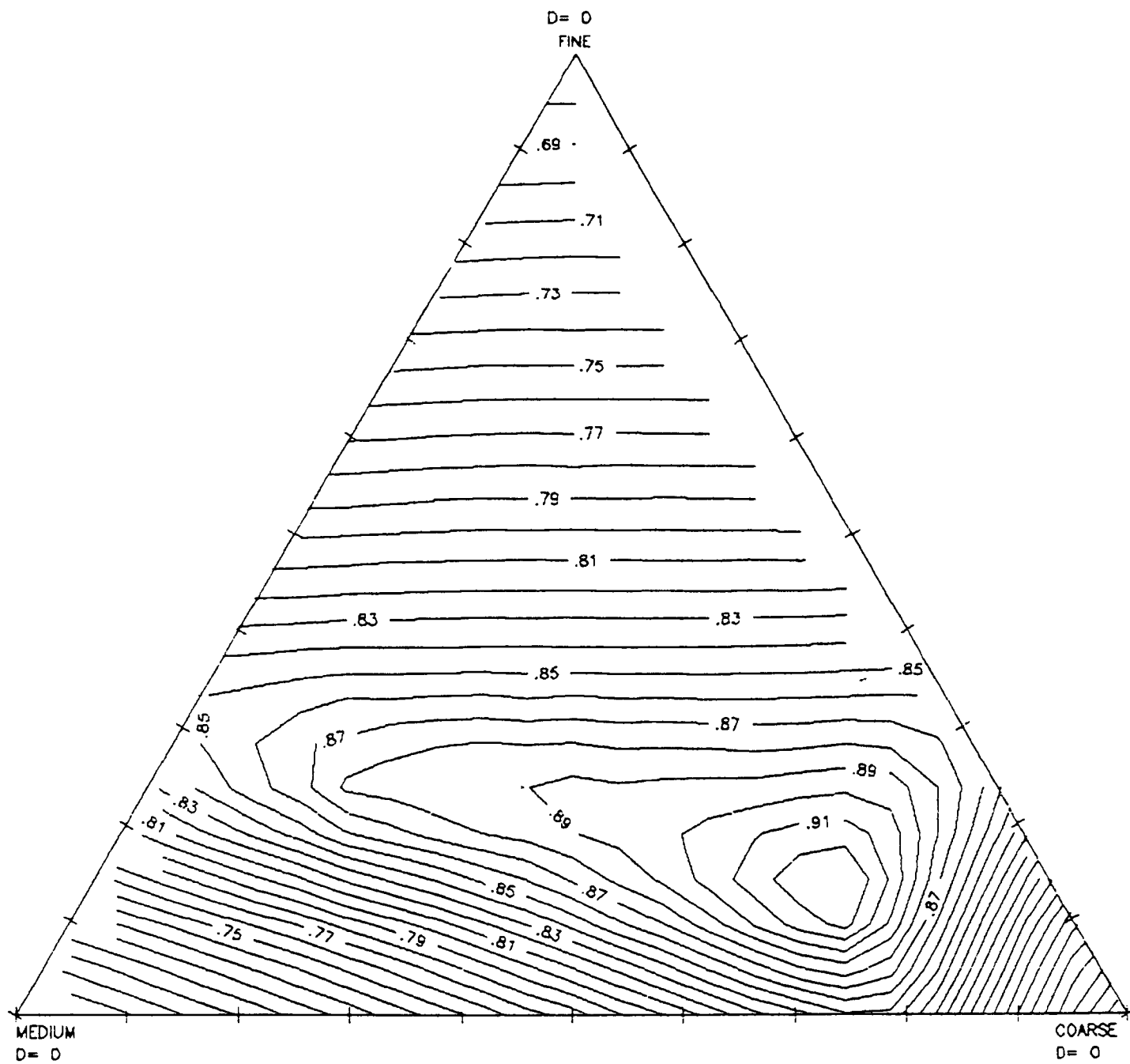


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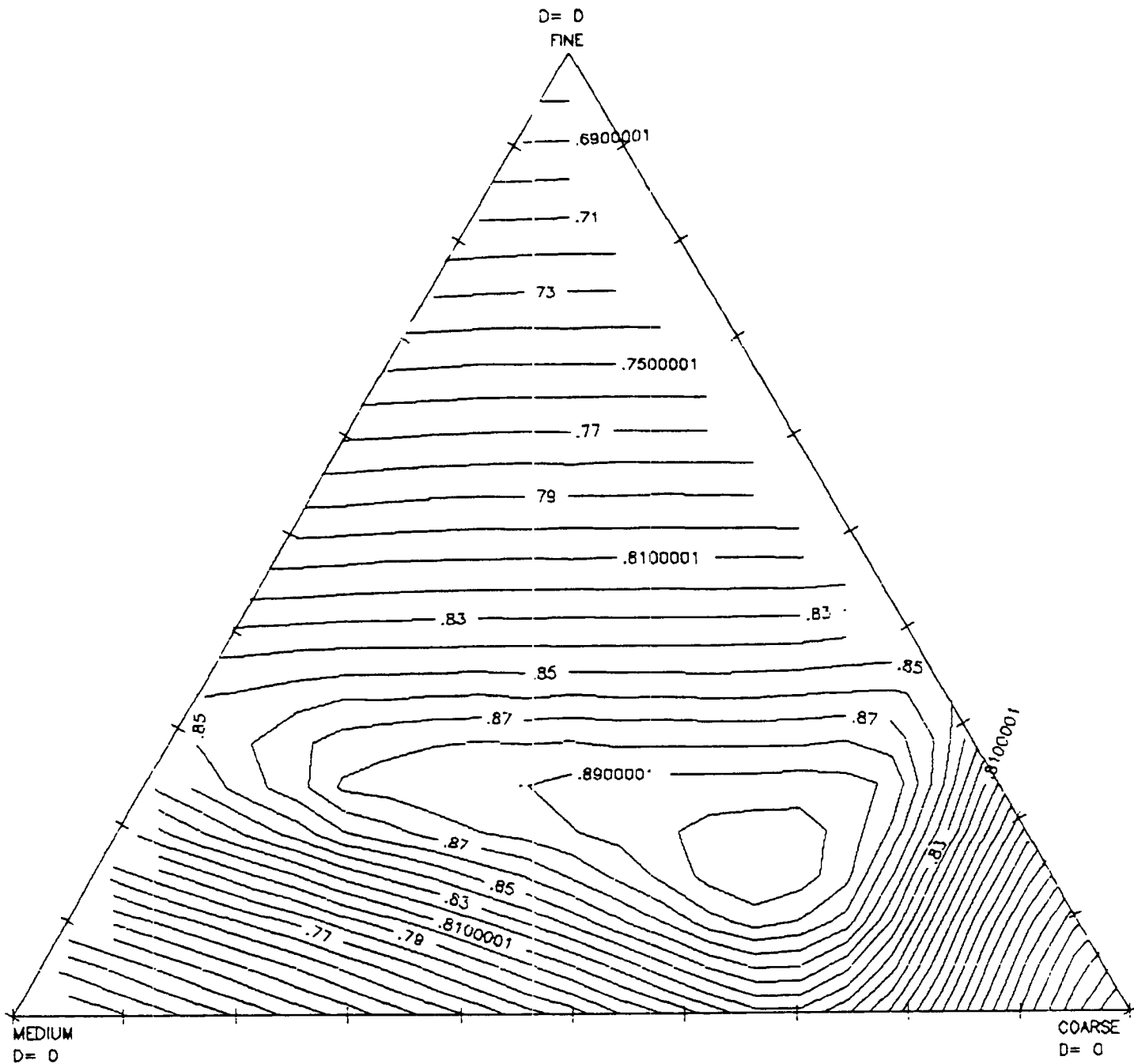


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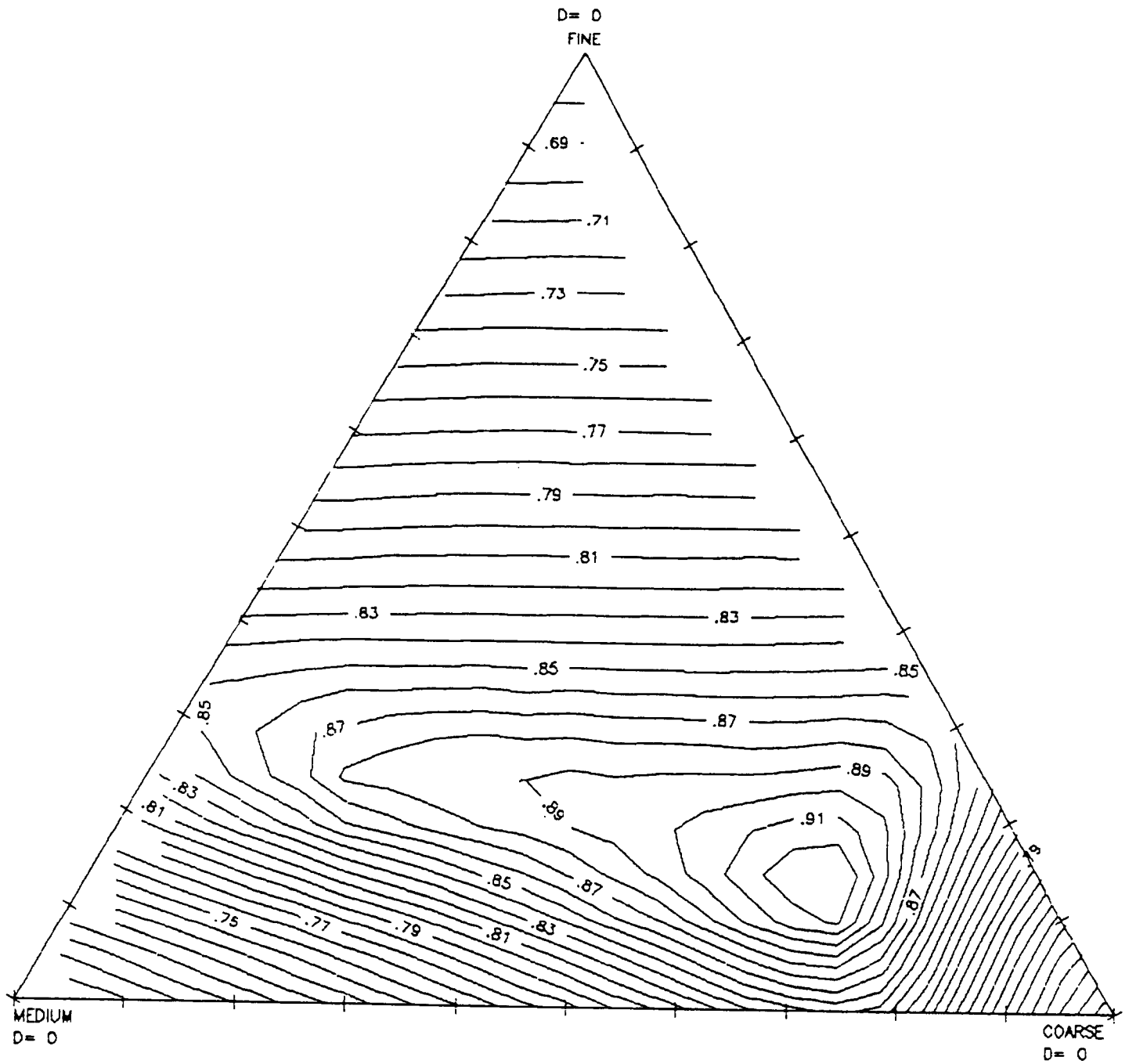




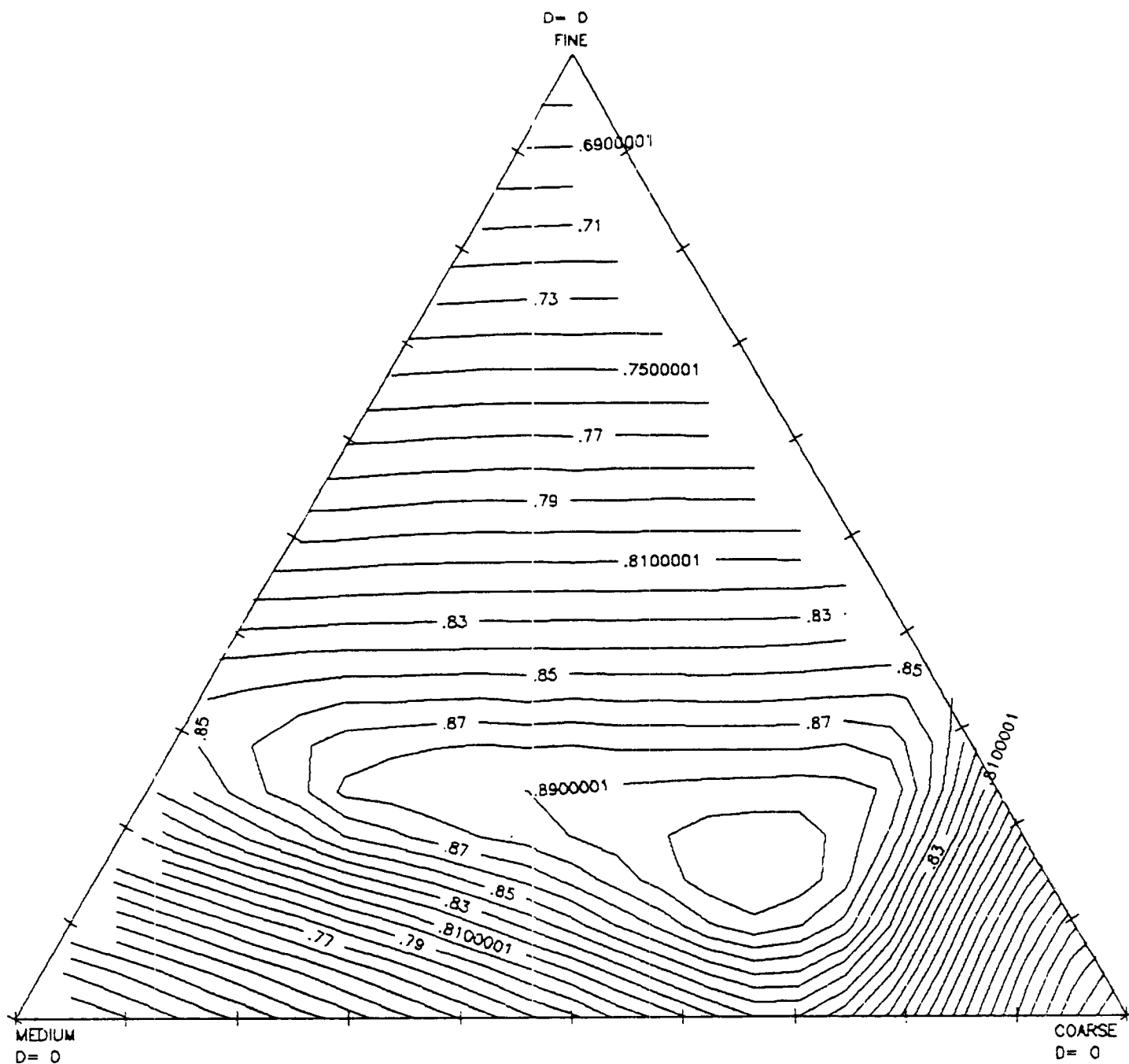
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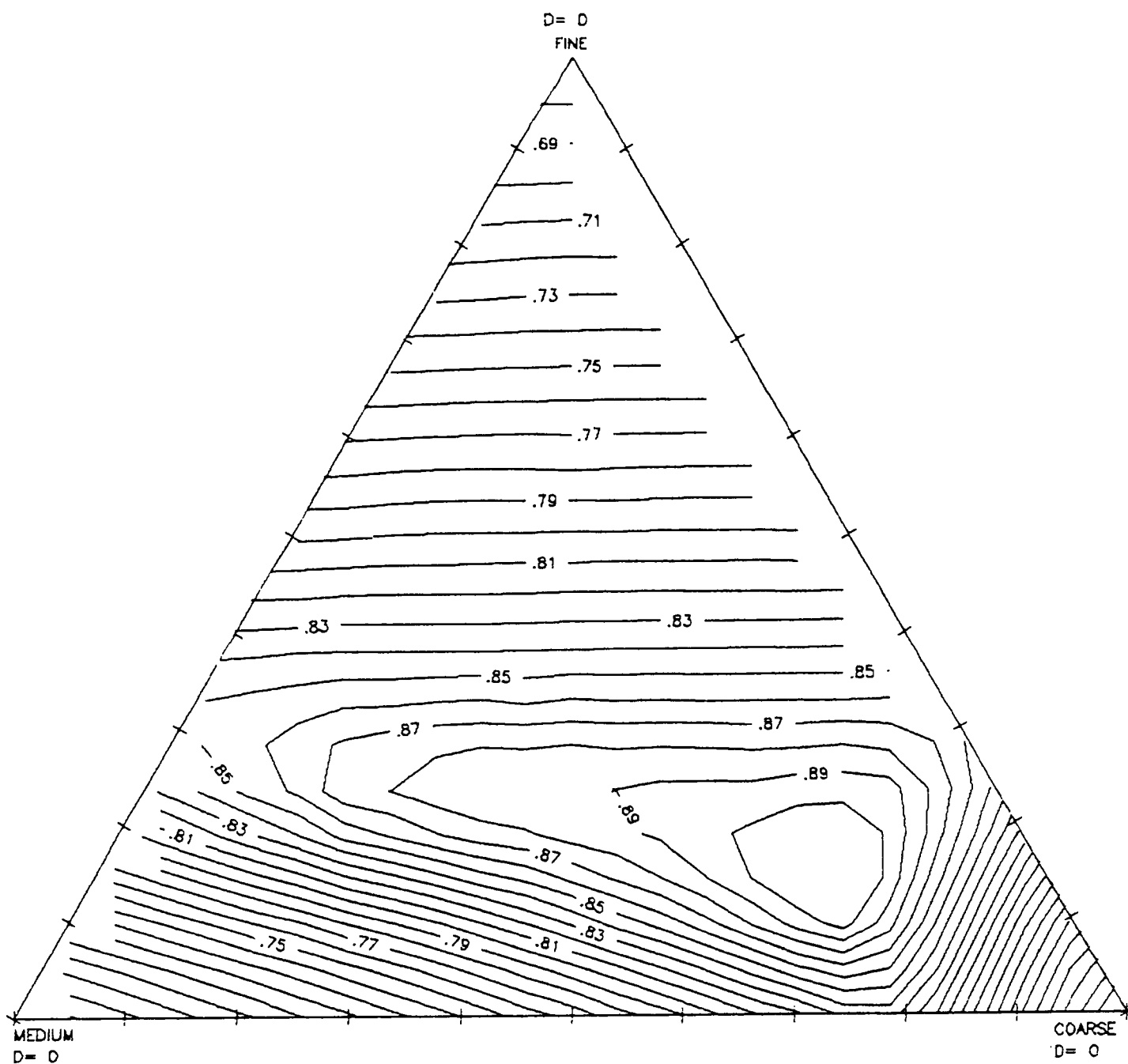
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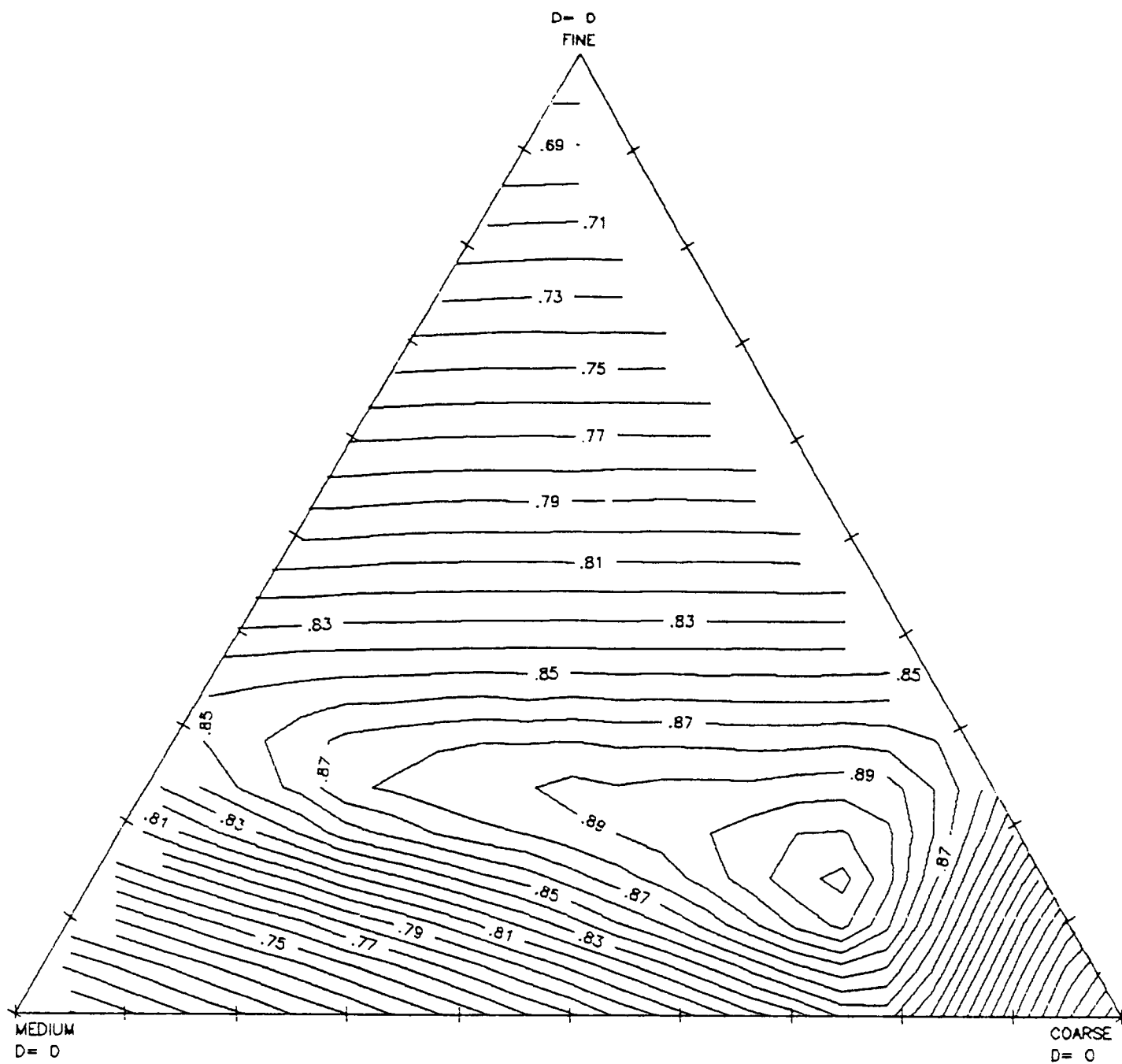
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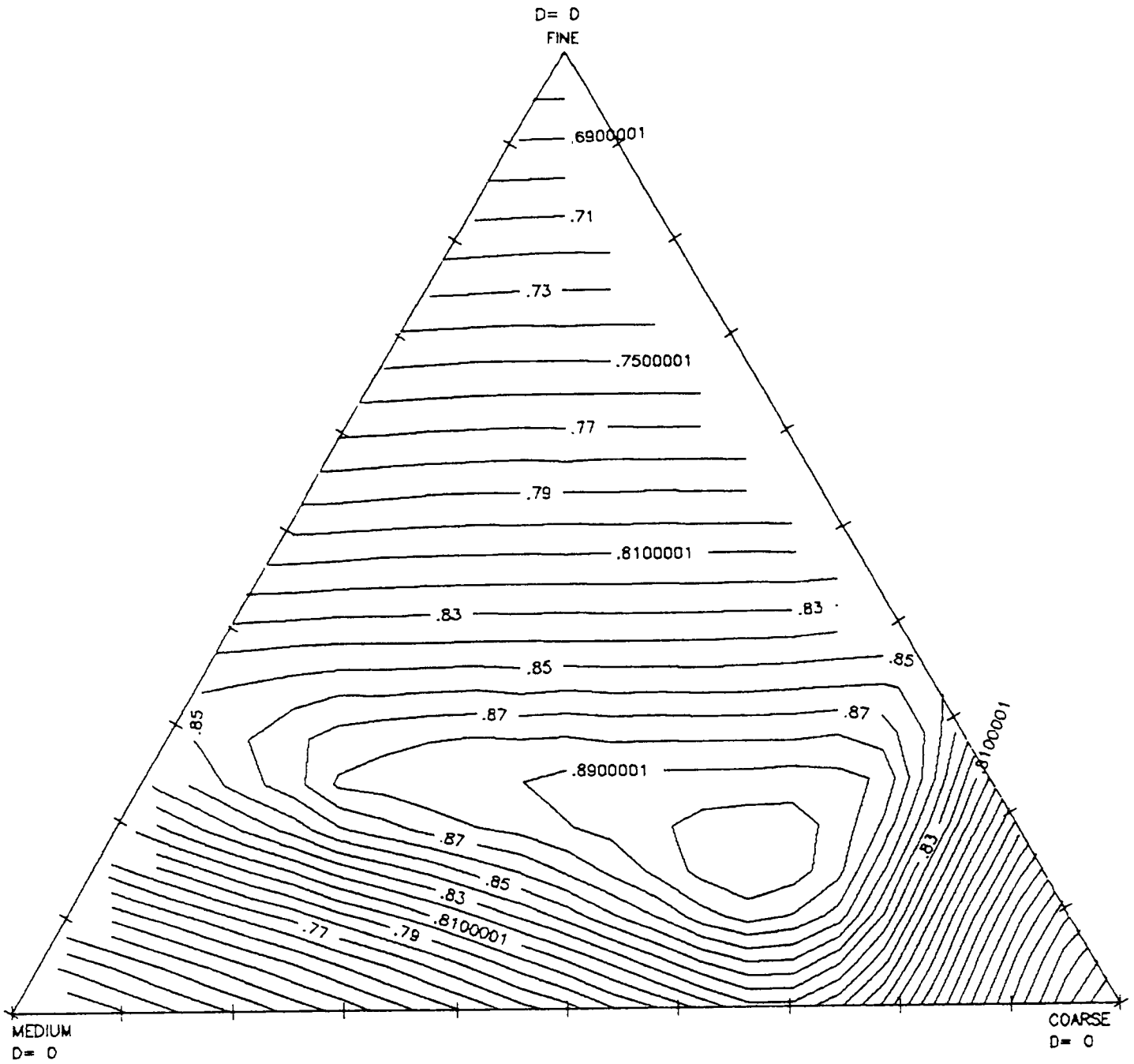
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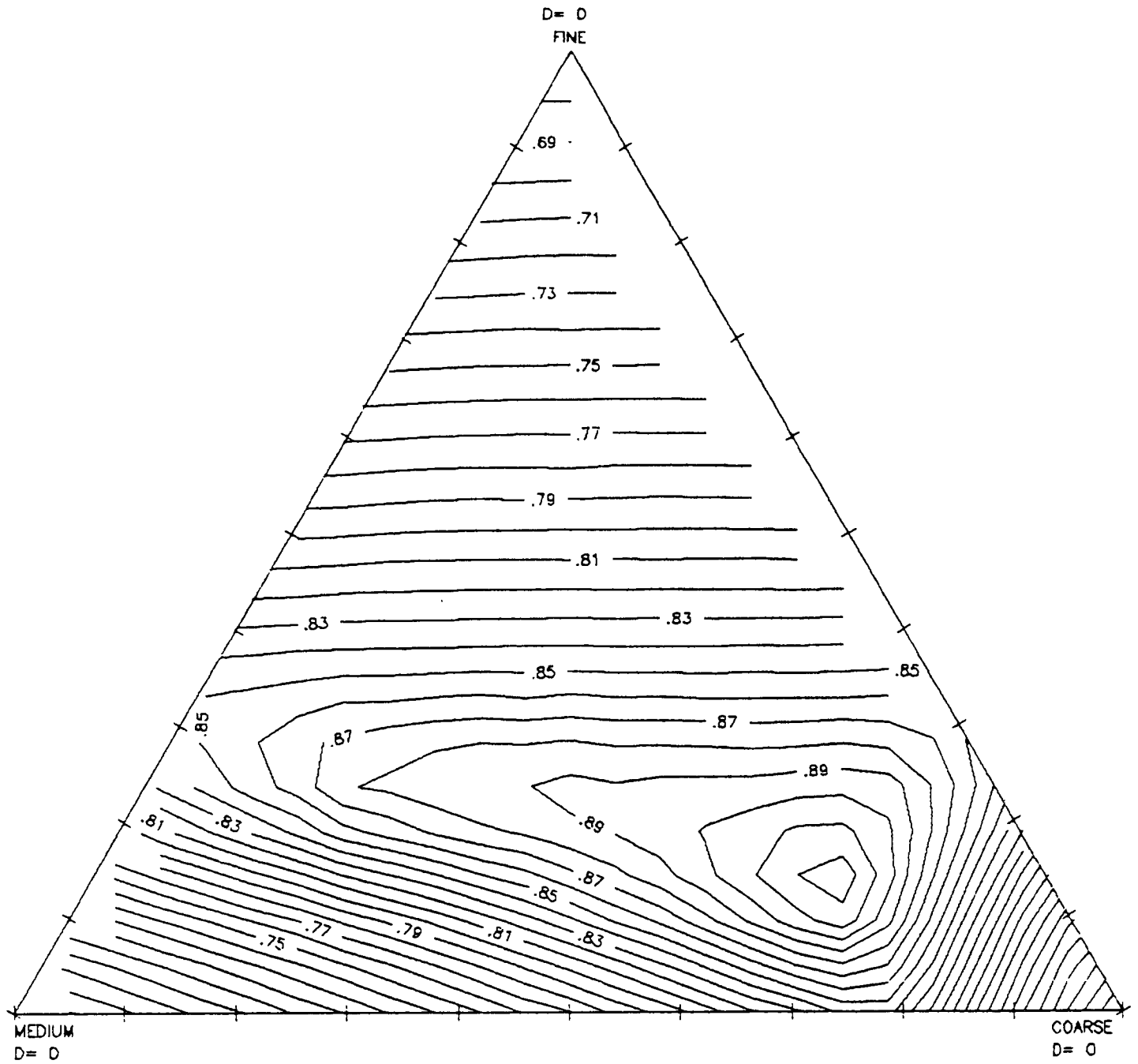
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67HL



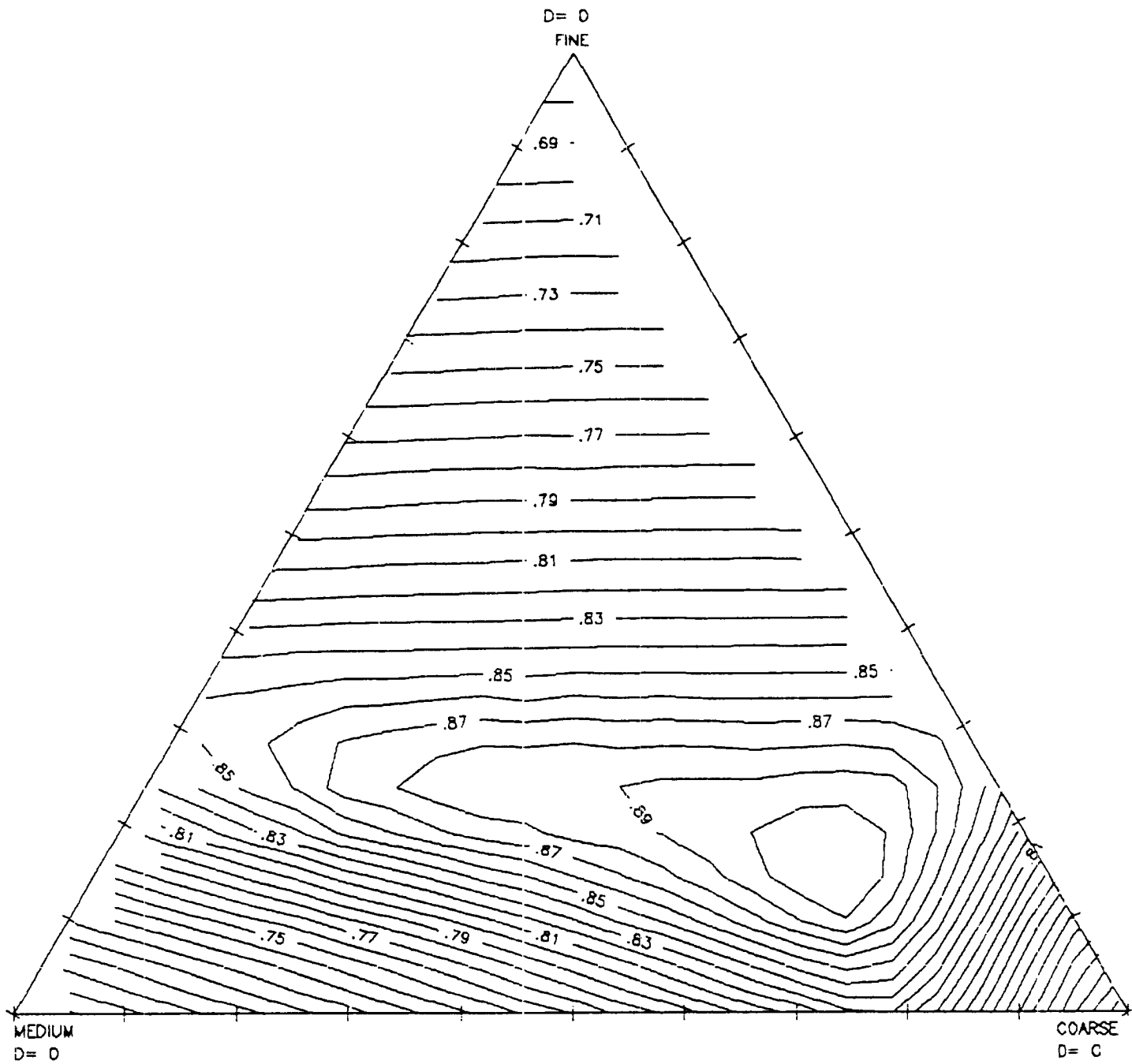
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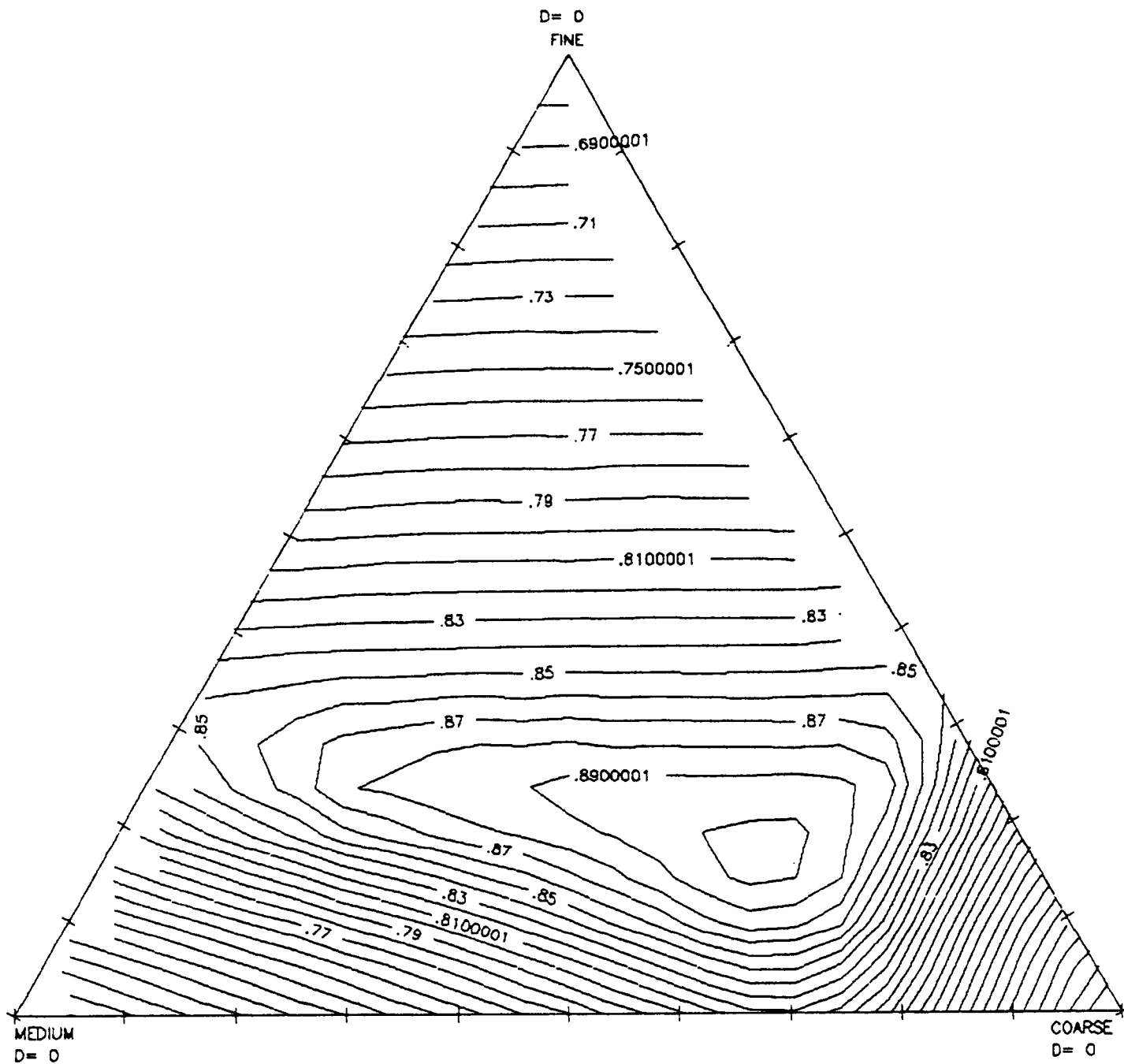
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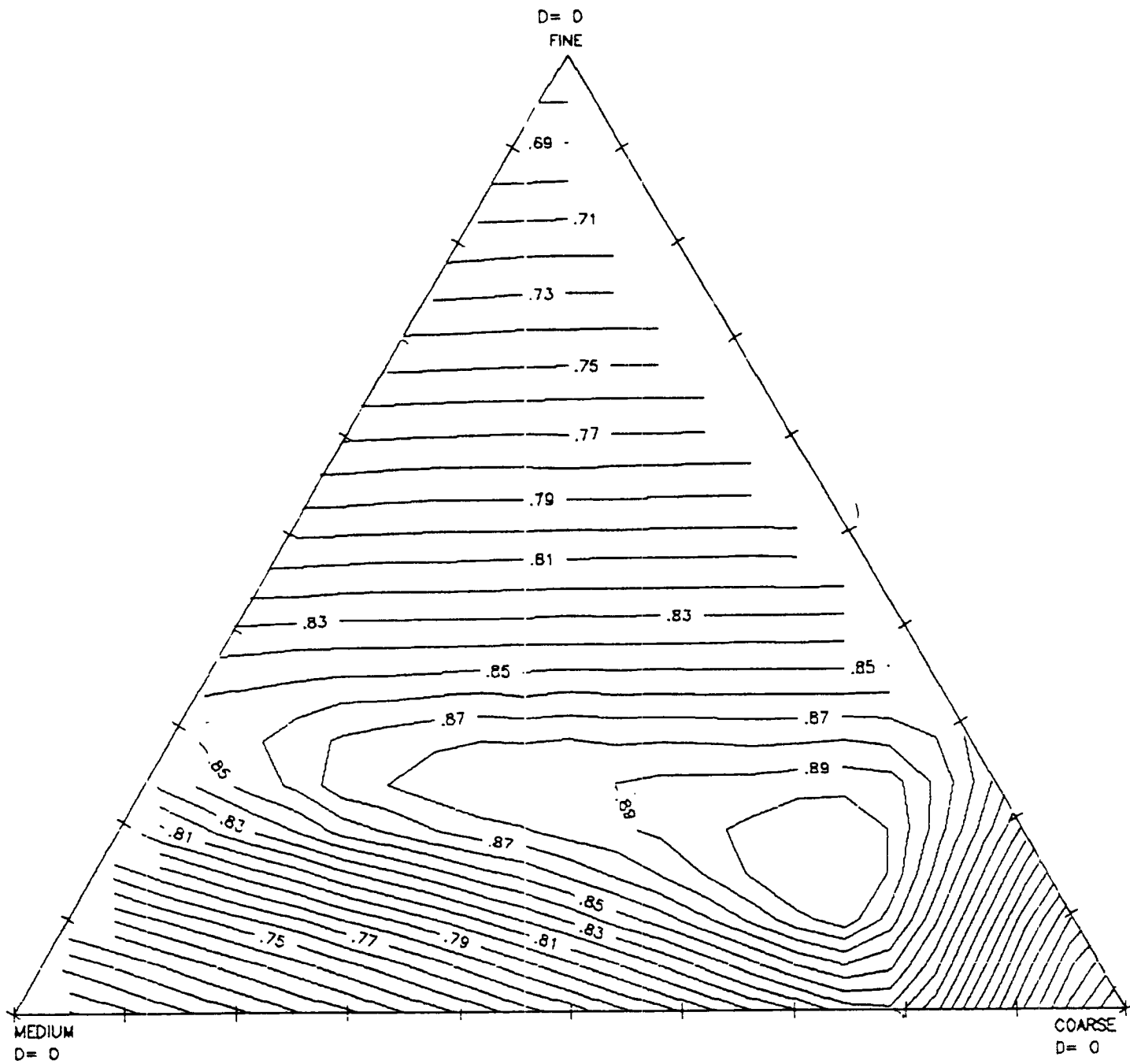




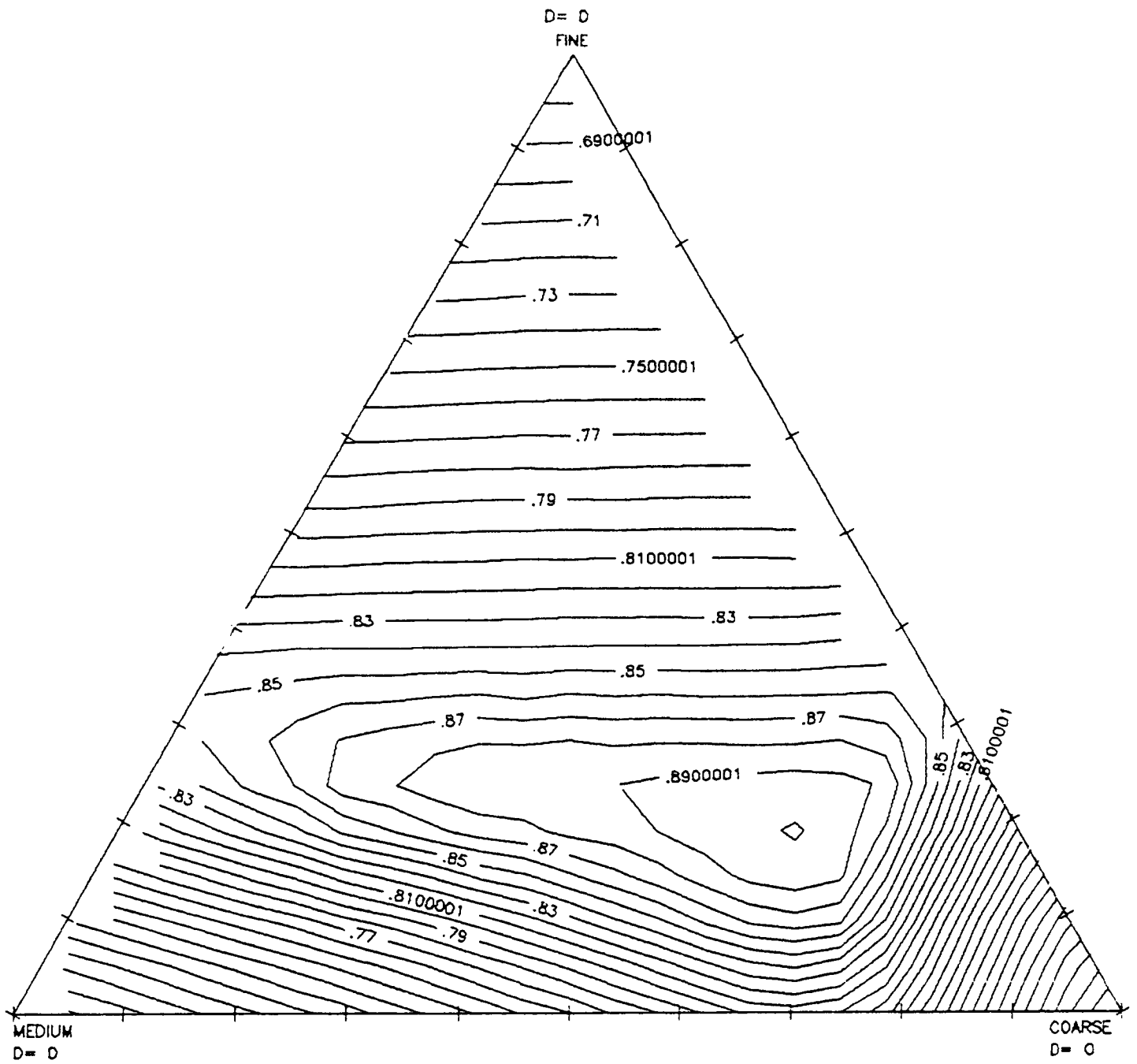
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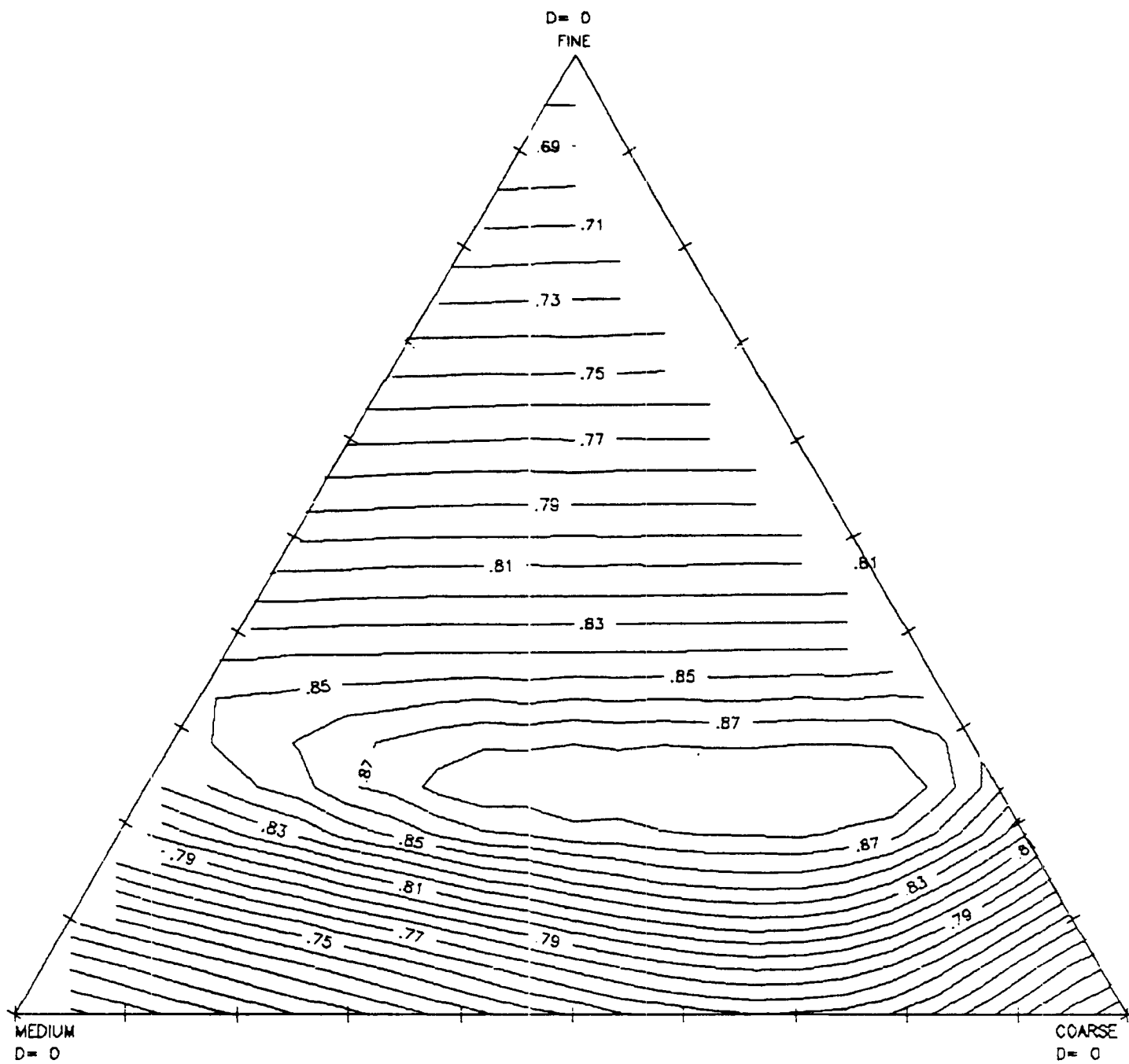
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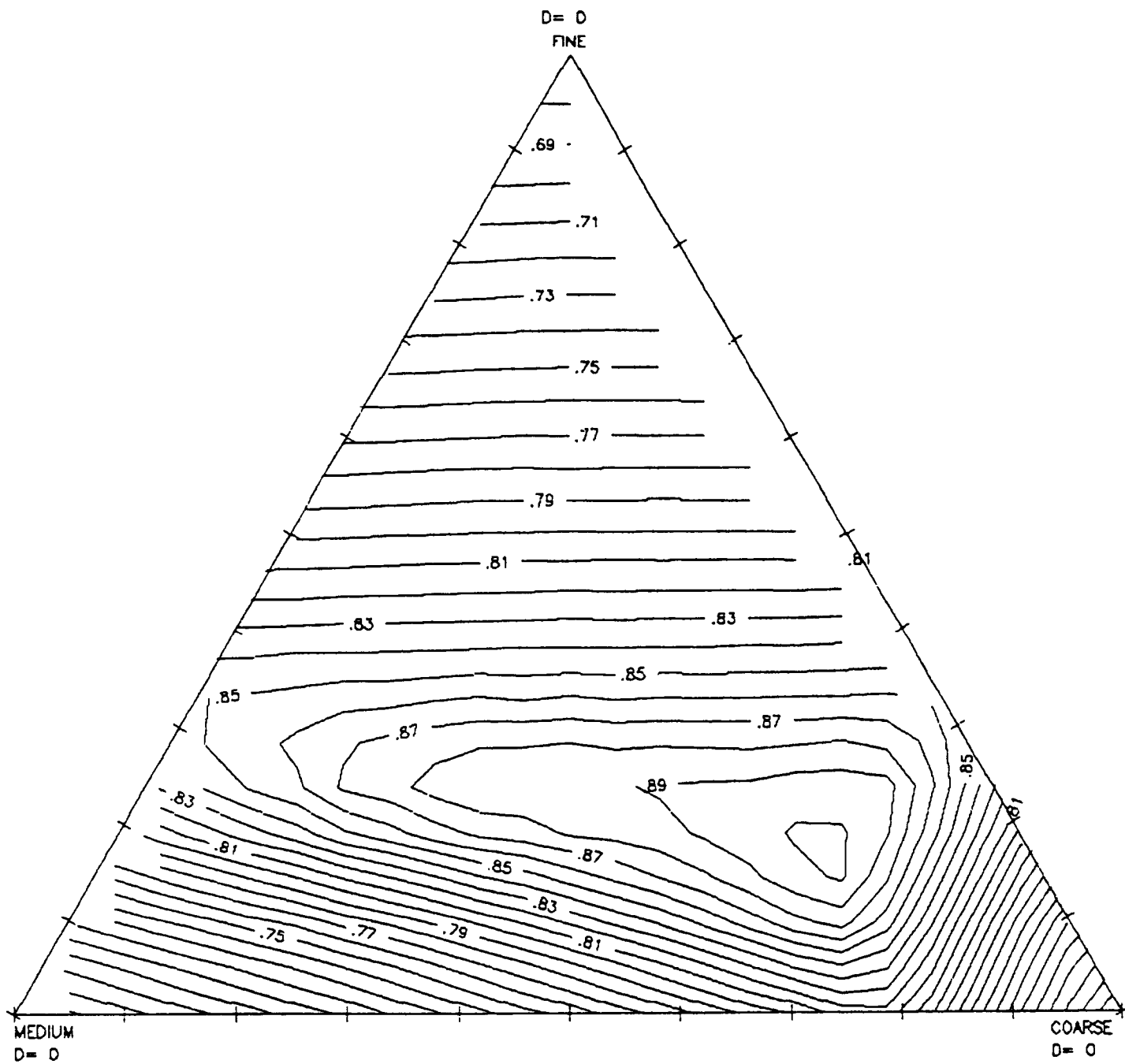
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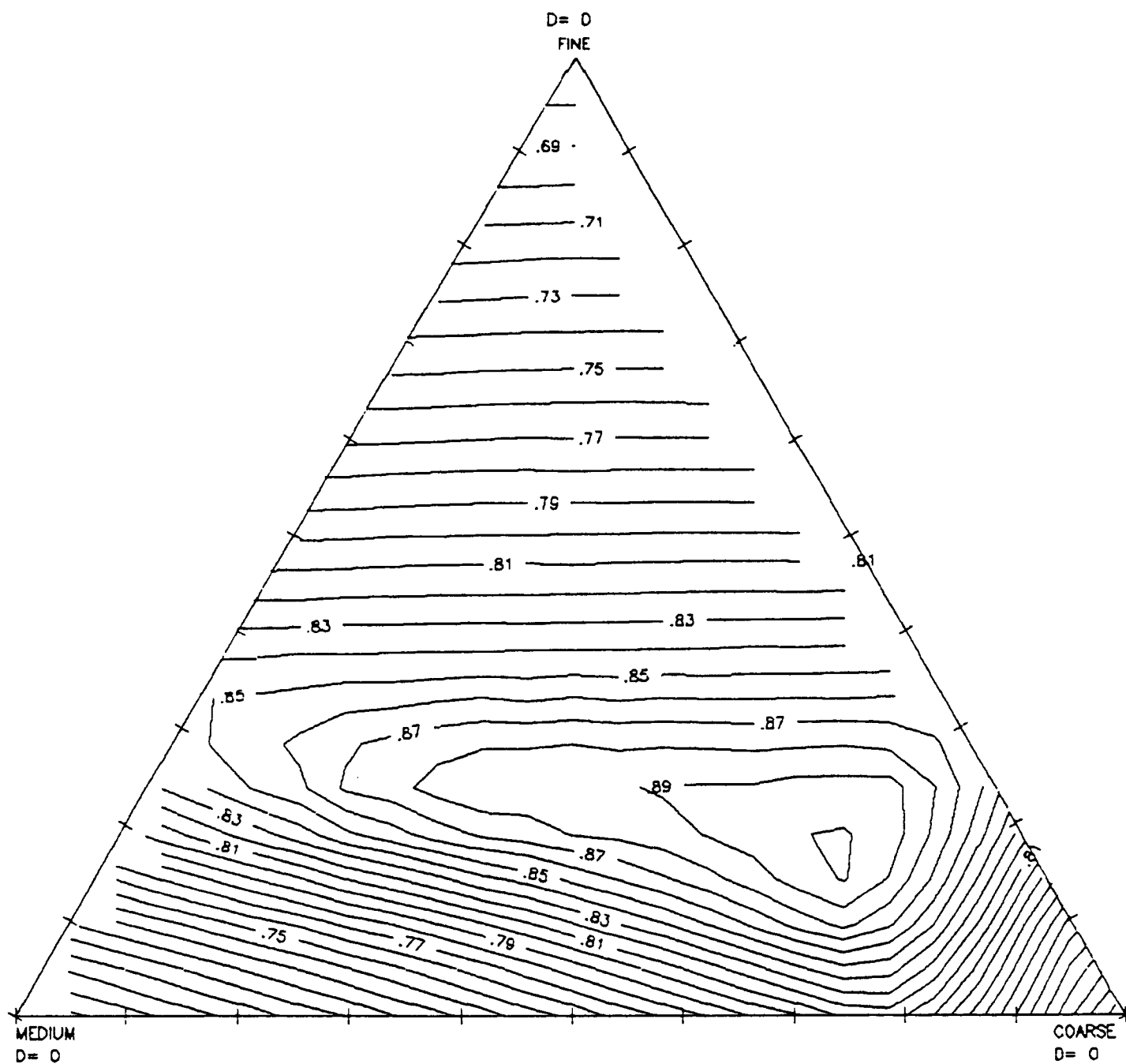


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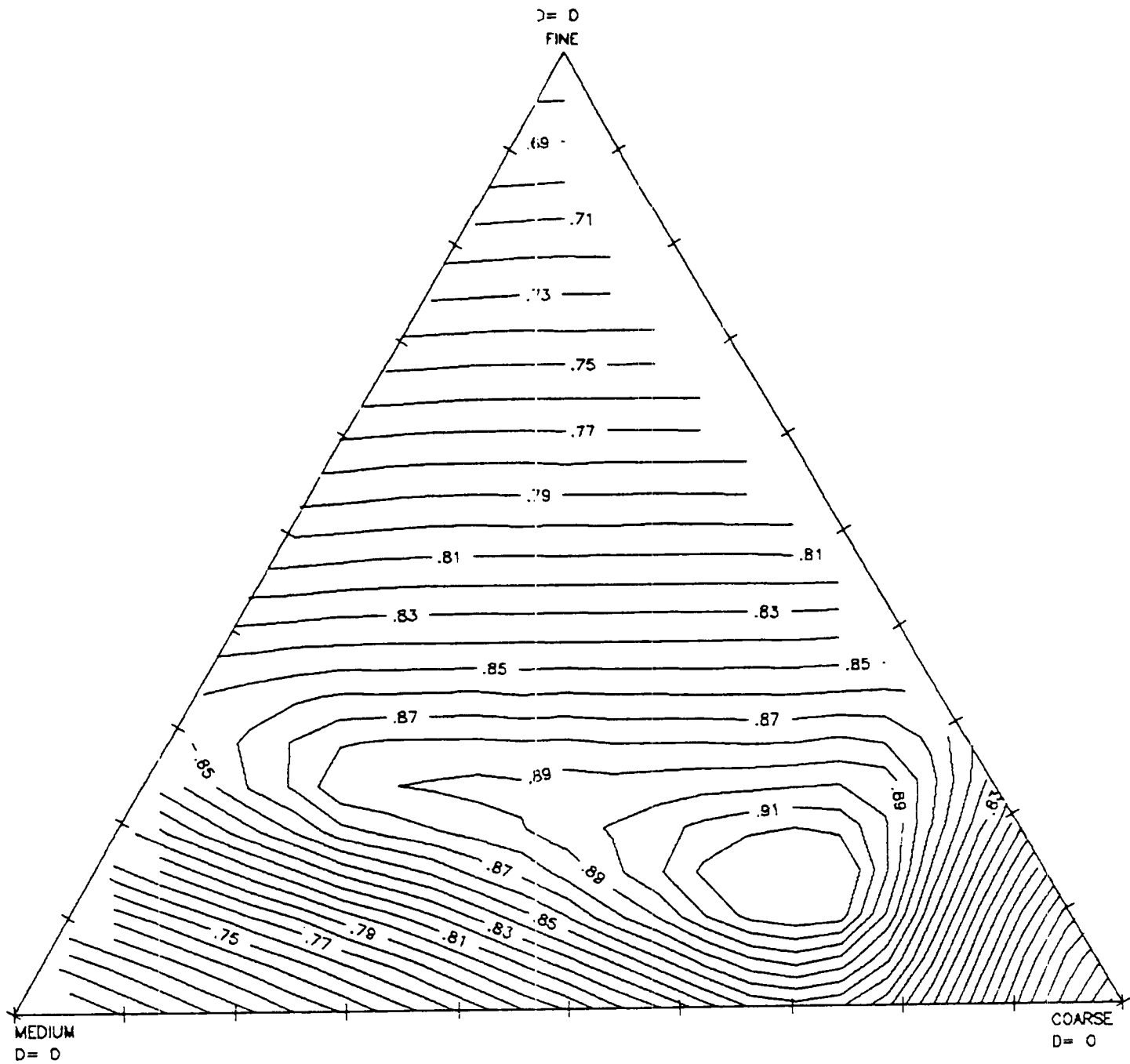




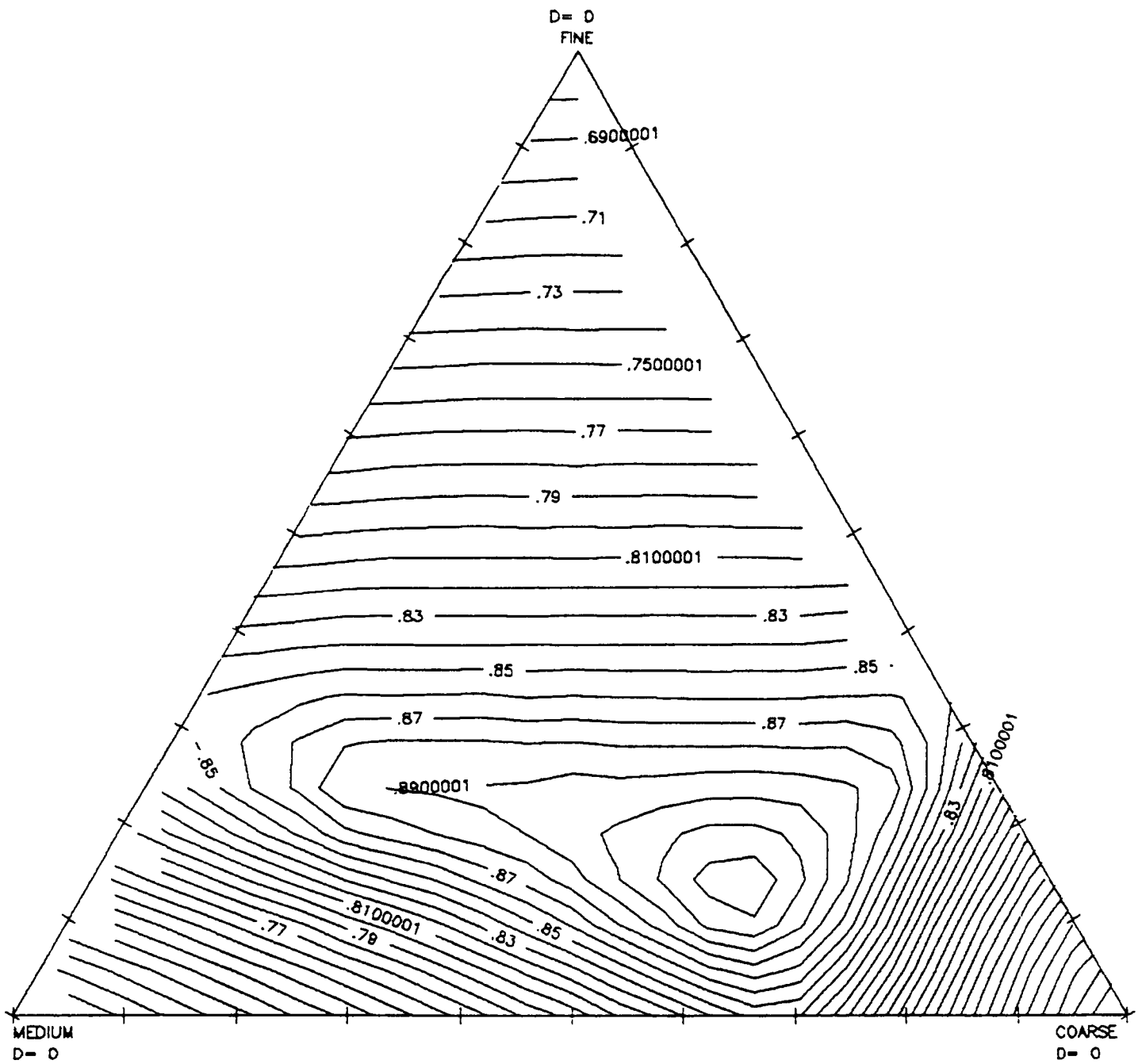




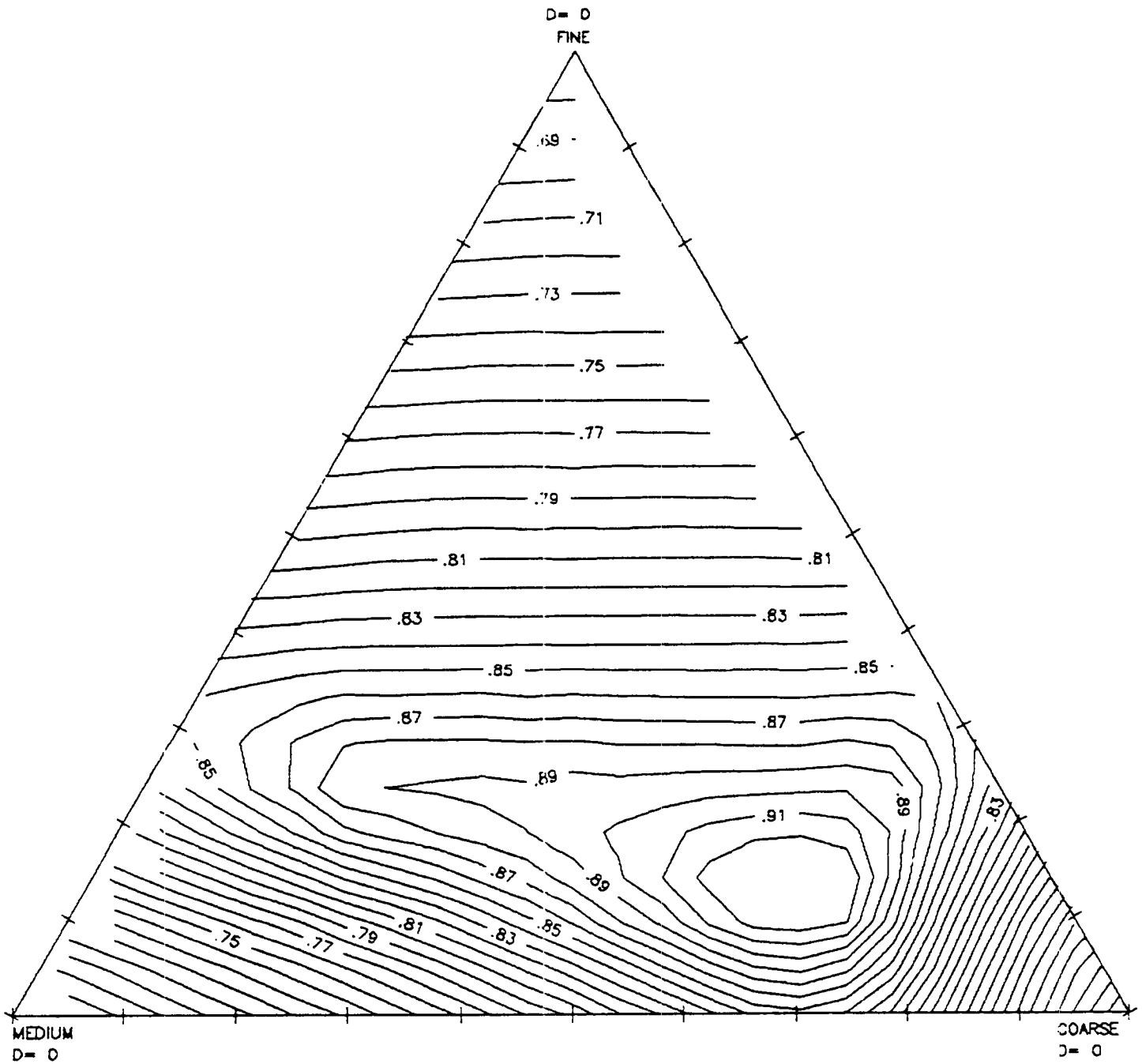
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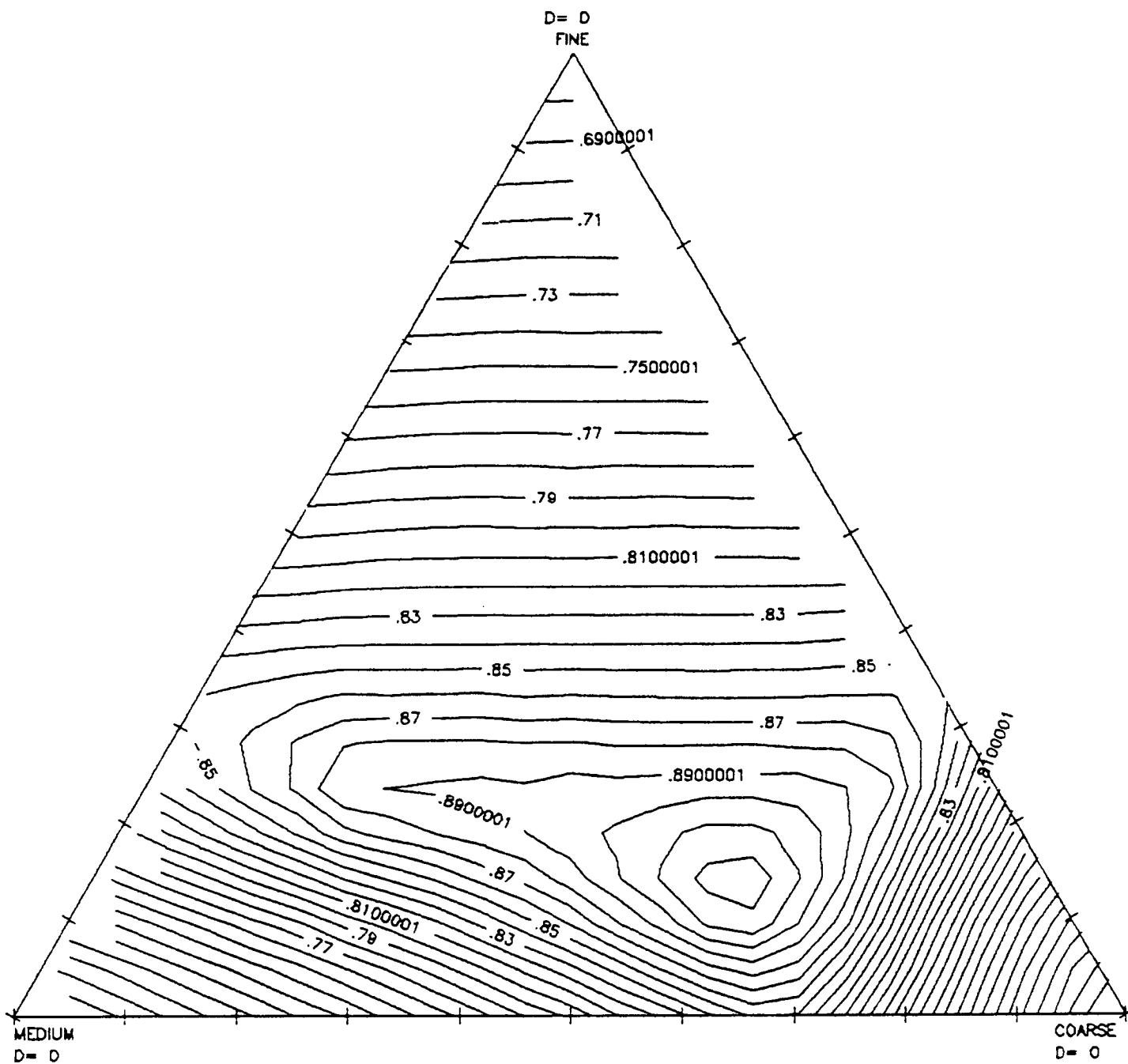
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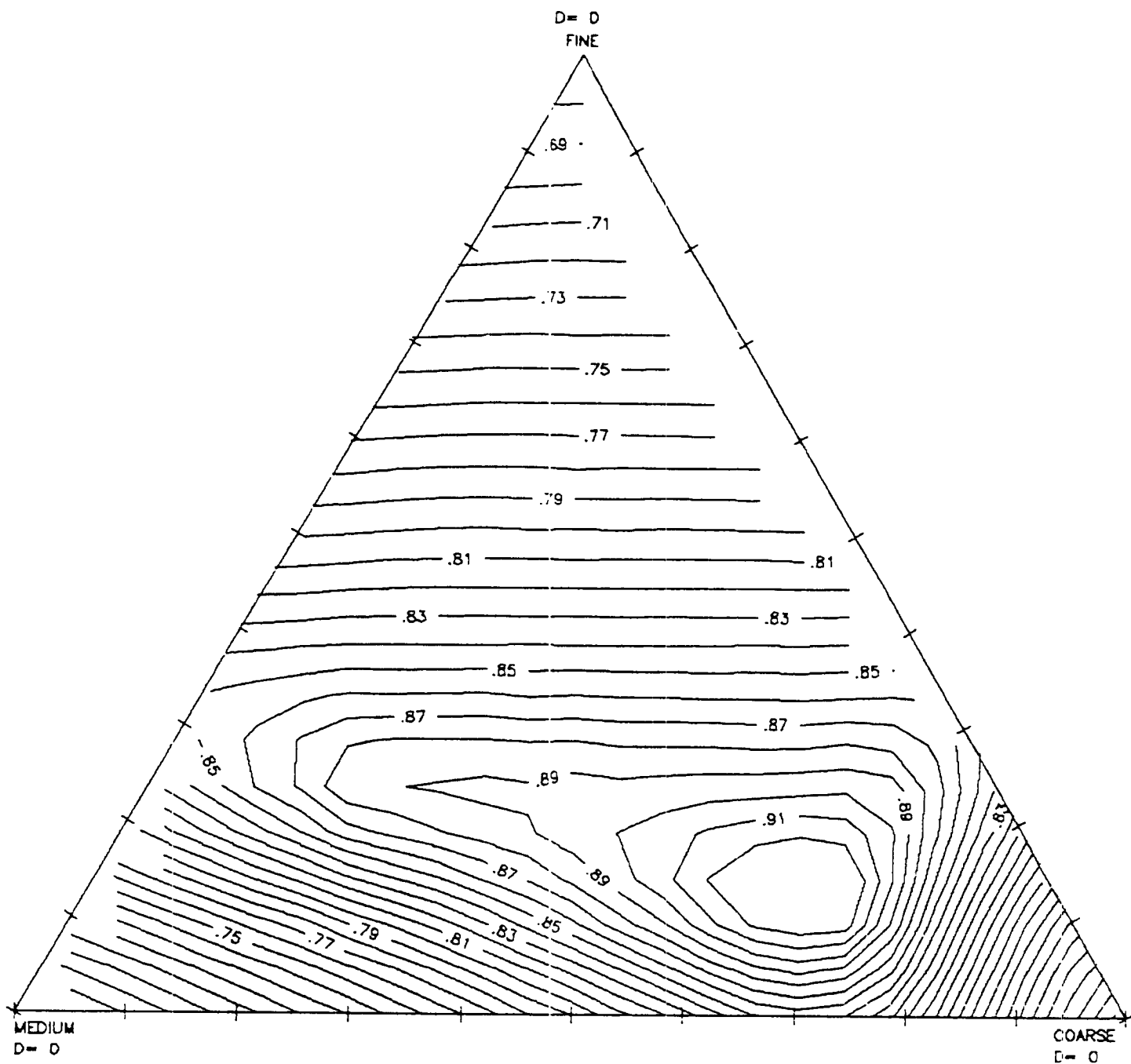
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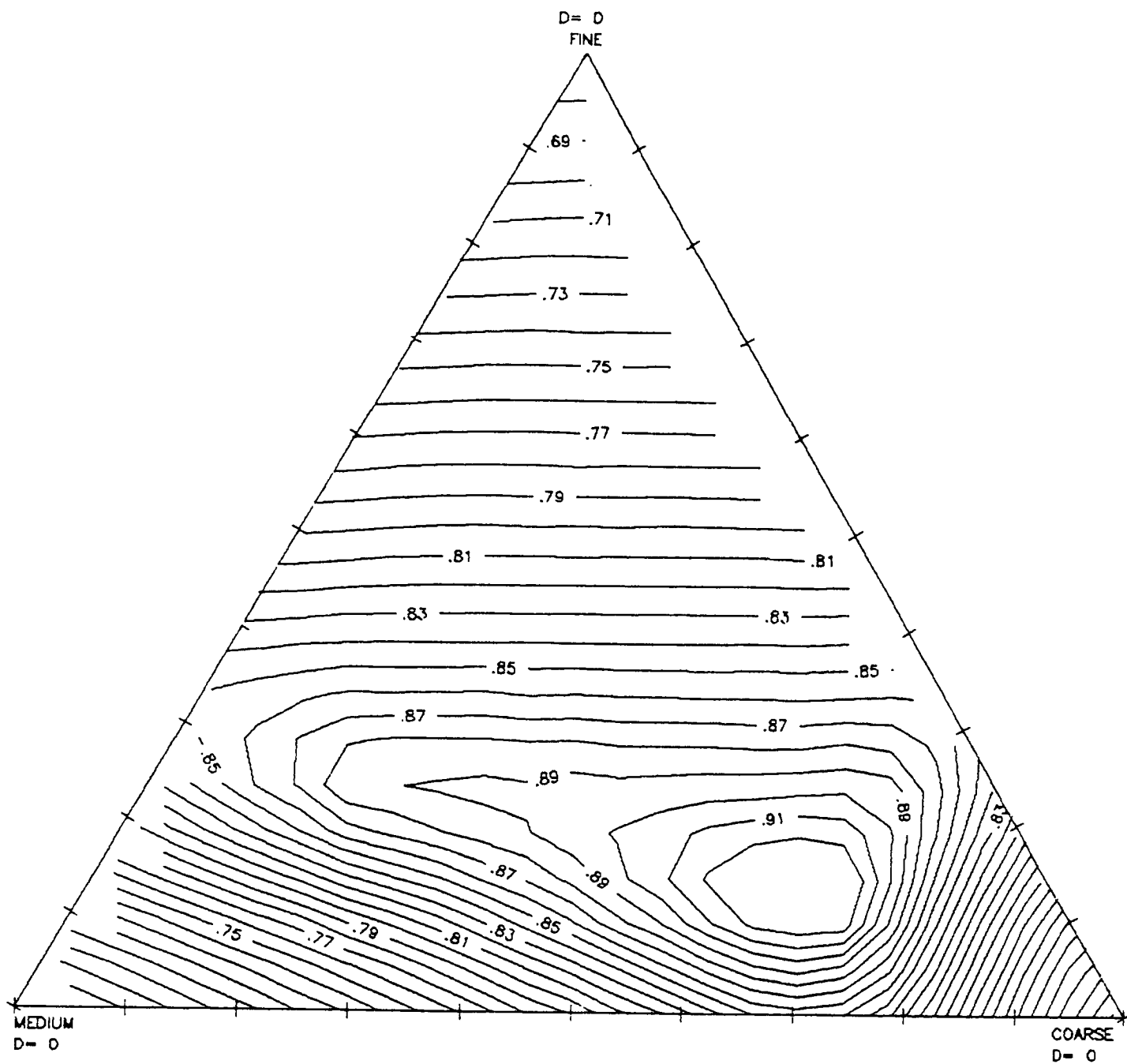
1ASIS



2H



2L



2LH

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