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SPLASH EVALUATION OF SRB DESIGNS

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16. ABSTRACT

A technique is developed to optimize the Shuttle solid rocket booster (SRB) design for water impact loads. The SRB is dropped by parachute and recovered at sea for reuse. Loads experienced at water impact are design critical. The probability of each water impact load is determined using a Monte-Carlo technique and an aerodynamic analysis of the SRB parachute system. Meteorological effects are included and four configurations are evaluated.

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BACKGROUND

The Shuttle Solid Rocket Booster (SRB) is designed for recovery at sea and reuse. When it impacts the water, it experiences loads that are highly dependent upon the conditions of water impact (velocity and angle). These conditions are a function of the meteorological conditions in the impact zone. Extremely high winds and seas have a certain probability of occurrence and designing for these worst-case loads potentially causes severe cost and weight penalties on the structure. Since the vehicle is not manned at time of impact, failures are purely economic. Designing for the worst-case load causes high program cost due to the resulting conservative design. Designing for a very frequent load results in a high program cost because of the large number of replacements required with the high attrition rate. Theoretically, the lowest program cost results from a lower per unit cost structure than the one designed for worst case and a lower attrition rate than that resulting from designing for no water impact loads.

Martin Marietta, under contract NAS8-29622, studied this problem and developed a computer program which investigated the attrition rate and costs associated with a specific design. The design variables were limited to the parachute descent velocity and whether the nozzle extension was jettisoned. At that time, the major attrition producing water impact load was slapdown.

Martin's computer program was installed on the MSFC computer and modified to update the loads and allow for analysis of various designs. It has been used to compute attrition rates of seven SRB configurations which are described herein.

PROGRAM DESCRIPTION

The Martin program is described in Volume II of the report Space Shuttle Solid Rocket Booster Recovery Systems Definition. It is a Monte Carlo analysis which treats the meteorological factors (wind, sea, etc.) and the strength of each element probabilistically. Each critical load condition is programmed as a table of loads input as a function of vertical velocity (V_V), horizontal velocity (V_H), and water impact angle (θ). For each Monte Carlo trial, a water impact condition (V_V, V_H, θ) is randomly selected and the set of loads is computed by interpolation from the tables. A set of strengths is randomly selected and compared to the loads. If a load exceeds its companion strength, a failure is tabulated. The percentage of failures is the attrition rate for that particular structure. Motor sinkage is indicated when the slapdown load exceeds the strength by a factor of 1.1 (the ratio of ultimate to yield strength for D6AC).

Using the Martin analysis technique, a new computer program, SPLASH, was written which presents the load probabilistically. It presents the entire curve instead of the sum of the failures (the value of the probability) at a certain strength level. These results can provide general information about a load and they can also be used as a design tool to evaluate a number of designs without additional computer runs. SPLASH can present design limit loads (predicted actual load with no factor of safety) or it can divide the load by a strength ratio probability distribution. The resulting curves are used directly with the predicted ultimate strength (no factor of safety) to determine the failure rate. The decision of whether to use the probability of strength is based on judgement, the failure mode, the kind of testing used, and the degree of conservatism desired.

The meteorological portion of the program has been updated to include the latest results of analyses[1,2,3]. Effects of high altitude wind gusts, low altitude wind gusts, wind shear, parachute release dynamics, and wave slope are all included. The conditional probability is computed for each contributor to the water impact condition so that high gusts will not result with low wind, etc. The wave slope computed is filtered to remove the effects of all waves with wave lengths smaller than an effective length unique for each type of loading. The filtering wave lengths used are vehicle length for slapdown, skirt diameter for cavity collapse, and nozzle diameter for nozzle and aft closure loads.

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1. SRB Attitude and Horizontal Velocity Probability Distributions at Water Impact. S&E-AERO-DD-6-74, MSFC, Mar. 4, 1974.

2. Natural Environment Inputs for the Monte Carlo Simulation of Sea Surface Angle for Shuttle SRB Attrition Studies. S&E-AERO-YA-17-74, MSFC, Mar. 27, 1974.

3. Estimation of SRB Coning Motion for Attrition Studies, S&E-AERO-DD-9-74, MSFC, May 3, 1974.

The actuator loads are a unique problem because of the azimuth orientation of the actuator relative to the horizontal velocity vector. To include this effect, an azimuth angle was selected randomly and the in-plane actuator load was multiplied by the sine of that angle.

The strength probability[4] is dependent upon the type of testing. The options for which data are available are no test, standard test, proof test, and model test. The results enclosed are for the standard test where a full size prototype or structural model is tested to the design limit load and corrections to the analytical model and the design are made as a result of any failures.

RESULTS

The strength probability distribution for standard test is shown in Figure 1, and the water impact conditions are shown in Figures 2 and 3. Note that 99 percent probability values of water impact are that the angle will be less than 12 deg and the horizontal velocity will be less than 19 m/sec (63 ft/sec).

Presented in Figures 4 through 18 are probability distributions for the significant water impact loads. In each case the appropriate wave slope filtering has been included and the curves with and without probability of strength are shown. Cases with and without the nozzle extension are plotted separately. To properly use the load curves, enter the curve with a design capability on the left and read the attrition rate on the top scale or the probability of nonexceedance on the bottom scale.

Generally, the probability of strength effect is to reduce the probability of failure for structures that have been designed for about 90 percent loads or less. For structures that have been designed for 3 sigma loads, the probability of low strength (less than 10 percent, Figure 1) will increase the failures when it is included and thus the curves tend to cross over on the right side.

The wave slope is added directly to the angle computed using wind and parachute dynamics. The effect of filtering the wave slope on the resulting angle can be seen in Figures 3 and 4. The filter length is based on judgement and was

4. Thomas, Jerrell and Hanagud, S.: Reliability-Based Econometrics of Aerospace Structural Systems: Design Criteria and Test Options. NASA TN D-7646, June 1974.

chosen upon the recommendation of D. Kross of MSFC. It assumes that the wave half length must be long enough to contribute to the dynamics and, therefore, must approximate the surface length over which the load acts. The effects of filtered wave slope on the load distribution are less dramatic than on the angle itself. The wave slope effects on all loads except cavity collapse and actuator were not visible on the plots.

A recent development in the meteorological investigations has been the introduction of coning effects. The parachute/SRB dynamics are three dimensional and include a nutational pendulum motion that combines rotation about several axes simultaneously. An additional problem is that the coning dynamics (rotation about the local vertical axis) have less damping associated with them so they increase the probability of higher angles associated with low horizontal velocities. Unfortunately, high angle and low velocity is a high load case for cavity collapse. Dynamics supplied by the Systems Dynamics Laboratory at MSFC[5] have been programmed for the nozzle and cavity collapse loads. The effects of wave slope and coning on the cavity collapse load can be seen in Figure 4. The distribution including all effects is plotted as a solid line and the load with wave slope and coning effects individually removed are plotted as dashed lines.

The cavity collapse loading case was a particular problem because the pressure distribution changed shape as well as peak value. Some of the loading conditions presented in MSFC document S&E-ASTN-ADL (74-38)[6] that had the highest peak pressures were not the most severe loading conditions. Because of this, the peak pressure (P_2) cannot be used as an indicator of failure. Several possible indicators were investigated. Lee load (the area under the pressure curve on the lee side) shows the best agreement with eigenvalues resulting from structural analyses and was used for the attrition rates computed.

The configurations evaluated are shown in Figures 19-22. Configuration 0 (Fig. 19) is the proposal configuration. Configuration 1 (Fig. 20) is a design that includes capability for cavity collapse. Configuration 1-1, modified (Fig. 21), has been optimized with the performance margin. Configuration 3 (Fig. 22) is a performance-only configuration that has the performance capability of

5. See footnote 3.

6. Updated SRB Cavity Collapse Water Impact Loads, Configuration Without Nozzle Extension. S&E-ASTN-ADL (74-38), MSFC, Apr. 26, 1974.

configuration 1-1 but has no weight or design for water impact loading. Tables 1 and 2 contain the results of comparing the capabilities of each configuration with the probability of loads. The capabilities and attrition rates are tabulated. In Table 2, maximum and minimum values are given based upon the following assumptions:

Actuator yield strength is 1112 kN (250 000 lb).

Actuator ultimate strength is 1334 kN (300 000 lb) (FTU)[7].

Nozzle ring yield at 1112 kN (250 000 lb) actuator force.

At 1334 kN (300 000 lb), nozzle is released to impact other structure resulting in the following attrition rates:

	Maximum	Minimum
Throat and Seal	FTU Rate	0.1 FTU Rate
Skirt	0.5 FTU Rate	0.05 FTU Rate
Closure	FTU Rate	0.1 FTU Rate
TVC Fluid Loop	FTU Rate	0.5 FTU Rate

COHERENT DESIGN REQUIREMENTS

The probability distributions can be used to establish coherent design requirements for water impact. Coherent requirements are requirements for each load that result in similar failure rates. They may or may not be realistic to design to, depending on the cost/attrition trade of each load, interrelationship between loads, and other factors. The following are coherent design requirements for 1 percent water impact attrition:

7. FTU means force tension ultimate.

	Factor of Safety Included	
	W/O Extension	With Extension
Slapdown	20 N/cm^2 (29 psi)	21 N/cm^2 (30 psi)
Submergence	17 N/cm^2 (25 psi)	18 N/cm^2 (26.7 psi)
Aft Closure Pressure	570 N/cm^2 (827 psi)	46 N/cm^2 (67 psi)
Cavity Collapse	1.33 × 100/15/0 Distribution	1.65 × 100/15/0 Distribution
Nozzle Side Load	1735 kN (390 000 lb)	3000 kN (675 000 lb)
Nozzle Axial Force	1557 kN (350 000 lb)	11.4 MN (2 570 000 lb)

ATTRITION PROGRAM

To use the results of the SPLASH program, another computer program was written[8] to compute the total number of units required. This program uses the mission model as supplied in the requirements documents. An attrition rate function that reduces with time and has an average attrition rate as found from the SPLASH program is input. The output includes the number of units required for the Shuttle program. The effects of refurbishment time, maximum life, and the variable launch rate are all included.

Tables 3 and 4 contain the total attrition rates and units required for 445 flights. The total attrition rate is 3 percent (for all nonwater impact causes) added to the individual structure failure rate plus the sinkage rate as shown in Tables 1 and 2. Where two numbers are given in Table 4, the larger number represents the maximum failure assumption for actuator cascading failure effects, and the smaller number is the minimum assumption. These numbers of required units can then be used in a cost analysis to compare the various designs and to determine the most effective design.

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8. Program was written by the Operations Development Branch of the Systems Analysis and Integration Laboratory at MSFC.

TABLE 1. WATER IMPACT ATTRITION RATES

Configuration	Slapdown		Submergence		Aft Closure		Cavity Collapse		Actuator		Sinkage	
	Capab. N/cm² (lb/in.²)	Rate	Capab. N/cm² (lb/in.²)	Rate	Capab. N/cm² (lb/in.²)	Rate	Capab. kN (lb × 10³)	Rate	Capab. kN (lb × 10³)	Rate	Capab. N/cm² (lb/in.²)	Rate
0	23.3 (33.8)	0.6	17.1 (24.8)	1	234 (340)	0.7	24.4 (5.48)	99.8	3570 (803)	0	25.6 (37.1)	0.44
0-X	23.3 (33.8)	0.7	17.1 (24.8)	2	2[illegible] (340)	0	24.4 (5.48)	99	1076 (242)	23.5	25.6 (37.1)	0.55
1	27 (39)	0.35	19.9 (28.8)	0.4	259 (375)	0.2	73.8 (16.6)	13.5	1700 (383)	1.25	29.6 (42.9)	0.26
1-X	27 (39)	0.35	19.9 (28.8)	0.4	259 (375)	0	73.8 (16.6)	26	756 (170)	38	29.6 (42.9)	0.4
1.1 Mod	29.8 (43.2)	0.25	22.0 (31.9)	~0.15	266 (383)	0.2	125 (28)	0.4	1780 (401)	0.85	[illegible].8 (47.5)	0.18
1.1-X	29.8 (43.2)	0.4	22.0 (31.9)	0	266 (383)	0	125 (28)	1.8	734 (165)	4[illegible]	32.8 (47.5)	0.3
3-X	27 (39)	0.5	21.0 (30.5)	0	259 (375)	0	36.9 (8.29)	94.6	756 (170)	38	29.6 (42.9)	0.4

Notes: 1. Rate values in percent.
2. Configurations with "-X" include nozzle extension. Others have had extension jettisoned.
3. Sinkage when slapdown load exceeds 1.1× strength.
4. Actuator capabilities are equivalent nozzle horizontal load for 1110 kN (250 000 lb) actuator load.

TABLE 2. ATTRITION RATES FOR ACTUATOR-INDUCED FAILURES

Configuration	Actuator Moment Arm m (in.)	Nozzle Pivot to End m (in.)	F_A/F_N	Nozzle Force Actuator Failure kN (lb × 10³)		Actuator	Nozzle Ring	Attrition Rates (%)							
								Throat and Seal		Skirt		Closure		TVC Fluid Loop	
				Yield	Ultimate			Max	Min	Max	Min	Max	Min	Max	Min
0	1.55 (61)	0.686 (27.0)	0.3115	3570 (803)	4290 (964)	0	0	0	0	0	0	0	0	0	0
0-X		2.21 (87.0)	1.033	1076 (242)	1290 (290)	23	23	17	1.7	8.5	0.9	17	1.7	17	1.7
1	1.71 (67.4)	1.32 (52.0)	0.6528	1700 (383)	2050 (460)	1.2	1.2	0.15	0	0	0	0.15	0	0.15	0
1-X		3.12 (123.0)	1.469	756 (170)	907 (204)	38	38	29	2.9	15	1.5	29	2.9	29	2.9
1.1	1.63 (54)	1.23 (48.4)	0.6234	1780 (401)	2140 (481)	0.8	0.8	0.08	0	0	0	0.08	0	0.08	0
1.1-X		3.16 (124.4)	1.569	707 (159)	845 (190)	42	42	33	3.3	17	1.7	33	3.3	33	3.3
3X	1.71 (67.4)	3.12 (123.0)	1.469	756 (170)	907 (204)	38	38	30	3	15	1.5	30	3	30	3

TABLE 3. TOTAL ATTRITION RATES (%)

			Configuration						
			0	0-X	1	1-X	1.1	1.1-X	3-X
SRM	Aft Cylinders		100	100	17	29	3.6	5.1	98
	Foward Cylinders		4	4.3	3.6	3.5	3.4	3.7	3.9
	Aft Closure	Max	3.4	21	3.4	32	3.3	36	33
		Min		5.3	3.3	6.3	3.2	6.6	6.4
	All Other Motor Seg.		3.4	3.6	3.3	3.4	3.2	3.3	3.4
	Nozzle Ring		3.4	27	4.5	41	4.0	45	41
	Nozzle Throat and Seal	Max	3.4	21	3.4	32	3.2	36	33
		Min		5.3	3.3	6.0		6.6	6.4
TVC	Actuator		3.4	27	4.5	41	4.0	45	41
	Power Supply	Max	3.4	21	3.4	32	3.2	36	33
		Min		5.3	3.3	6.0		6.6	6.4
Structures	Aft Skirt	Max	3.4	12	3.3	18	3.2	20	18
		Min		4.5		4.9		5.0	4.9
	ET Attach Ring		3.4	3.6	3.3	3.4	3.2	3.3	3.4
	Other Structures		3.4	3.6	3.3	3.4	3.2	3.3	3.4
E&I			3.4	3.6	3.3	3.4	3.2	3.3	3.4
Recovery			8	8	8	8	8	8	8

TABLE 4. TOTAL SHIP SETS REQUIRED

			Configuration							Max Uses	Turn-around
			0	0-X	1	1-X	1.1	1.1-X	3-X		
SRM	Aft Cylinders		890	890	172	264	72	83	874	20	120
SRM	Forward Cylinders		85	77	72	73	70	72	74	20	120
SRM	Aft Closure	Max	70	202	70	288	70	319	296	20	120
		Min		84		91		94	92		
SRM	All Other Motor Seg.		70	72	70	70	70	70	70	20	120
SRM	Nozzle Ring		70	249	78	359	75	390	359	20	120
SRM	Nozzle Throat and Seal	Max	70	202	70	288	70	319	296	20	120
		Min		84		91		94	92		
TVC	Actuator		95	260	102	362	99	392	362	20	56
TVC	Power Supply	Max	95	216	95	295	94	325	303	20	56
		Min		107	94	111		116	115		
Structures	Aft Skirt	Max	53	121	53	169	52	185	169	40	56
		Min		62		65		66	65		
Structures	ET Attach Ring		52	53	51	52	50	51	52	40	46
Structures	Other Structures		53	55	53	53	52	53	53	40	56
E&I			72	73	71	72	71	71	72	20	56
Recovery			139	139	139	139	139	139	139	10	60

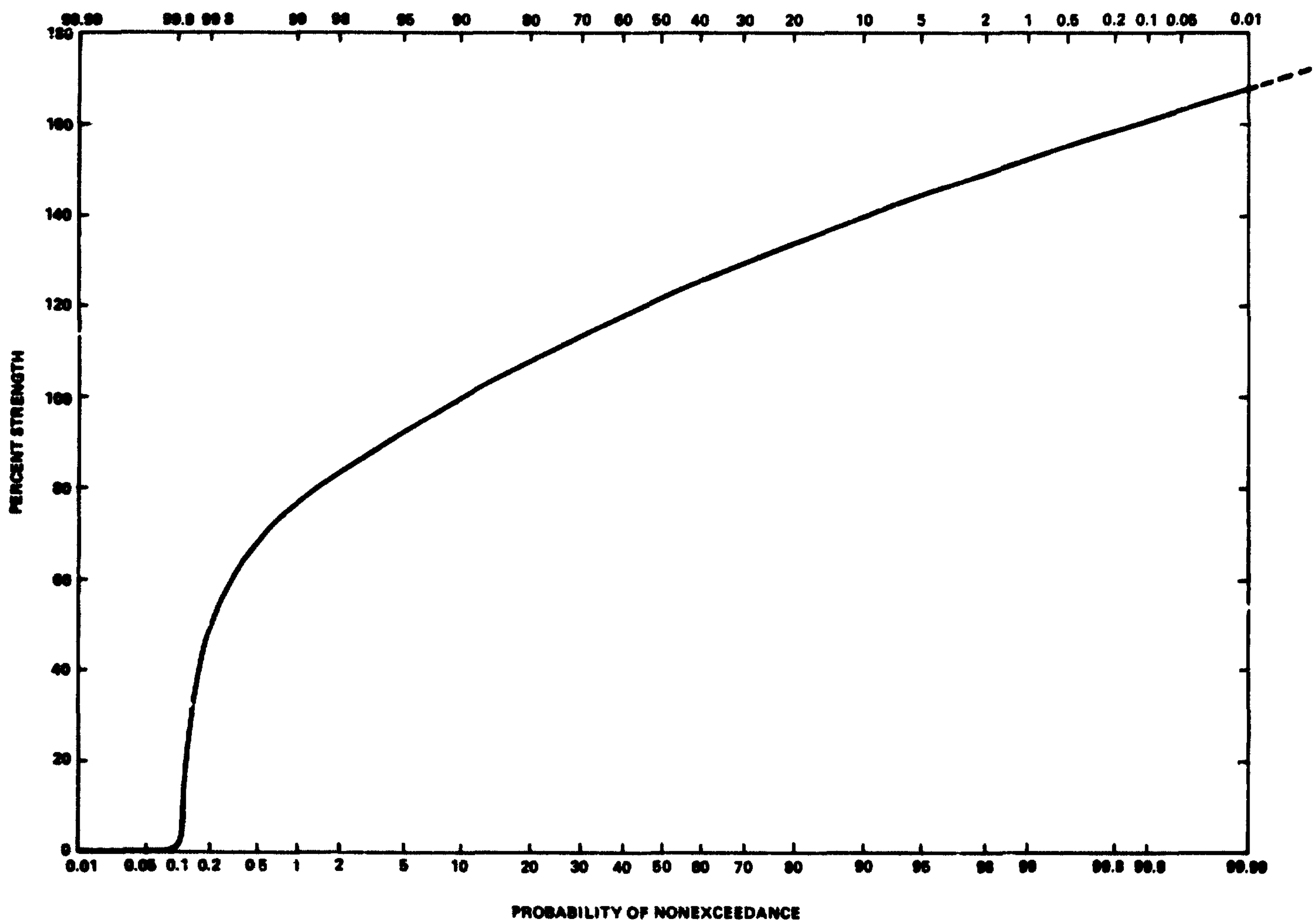


Figure 1. Probability of strength, standard test.

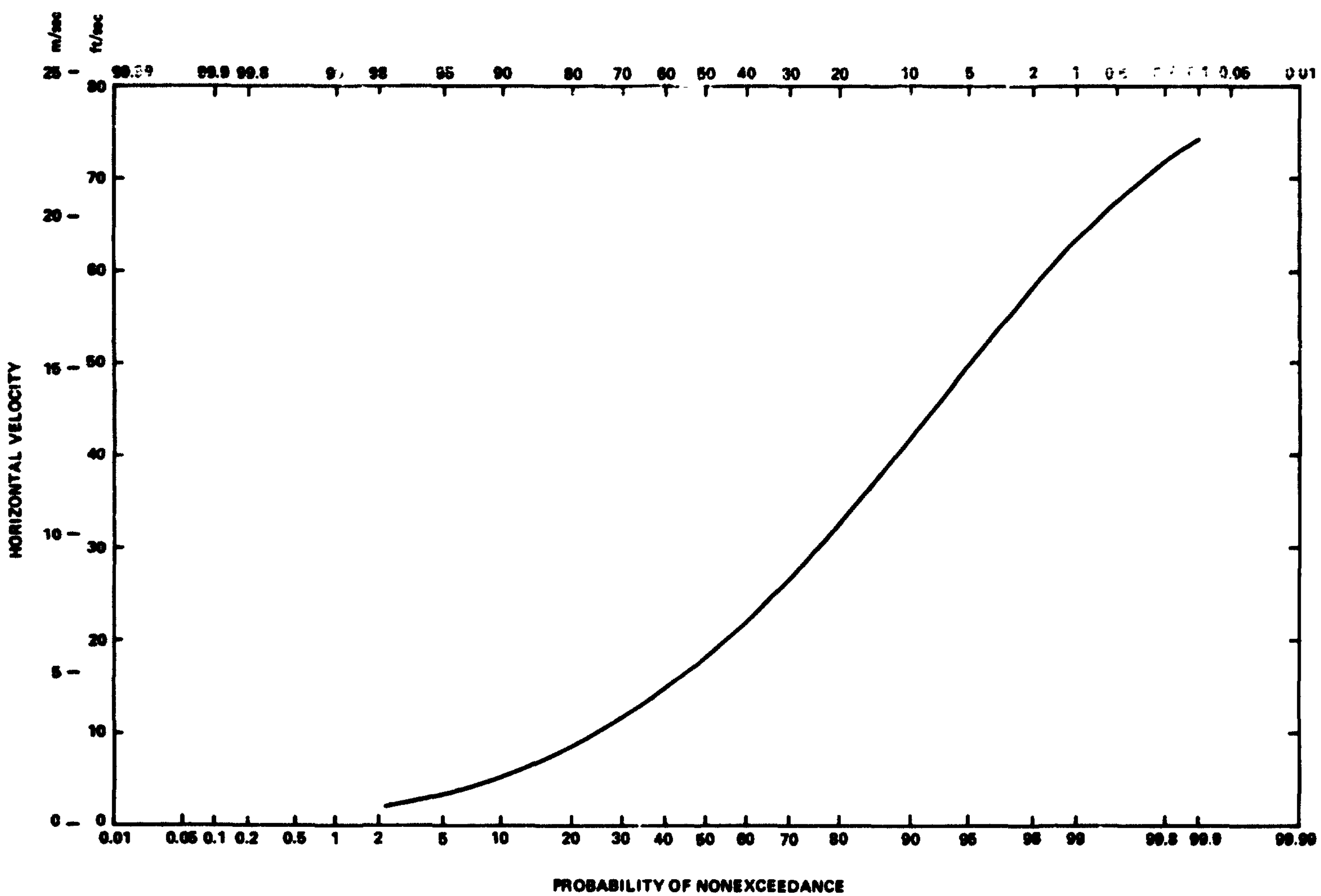


Figure 2. Horizontal velocity probability.

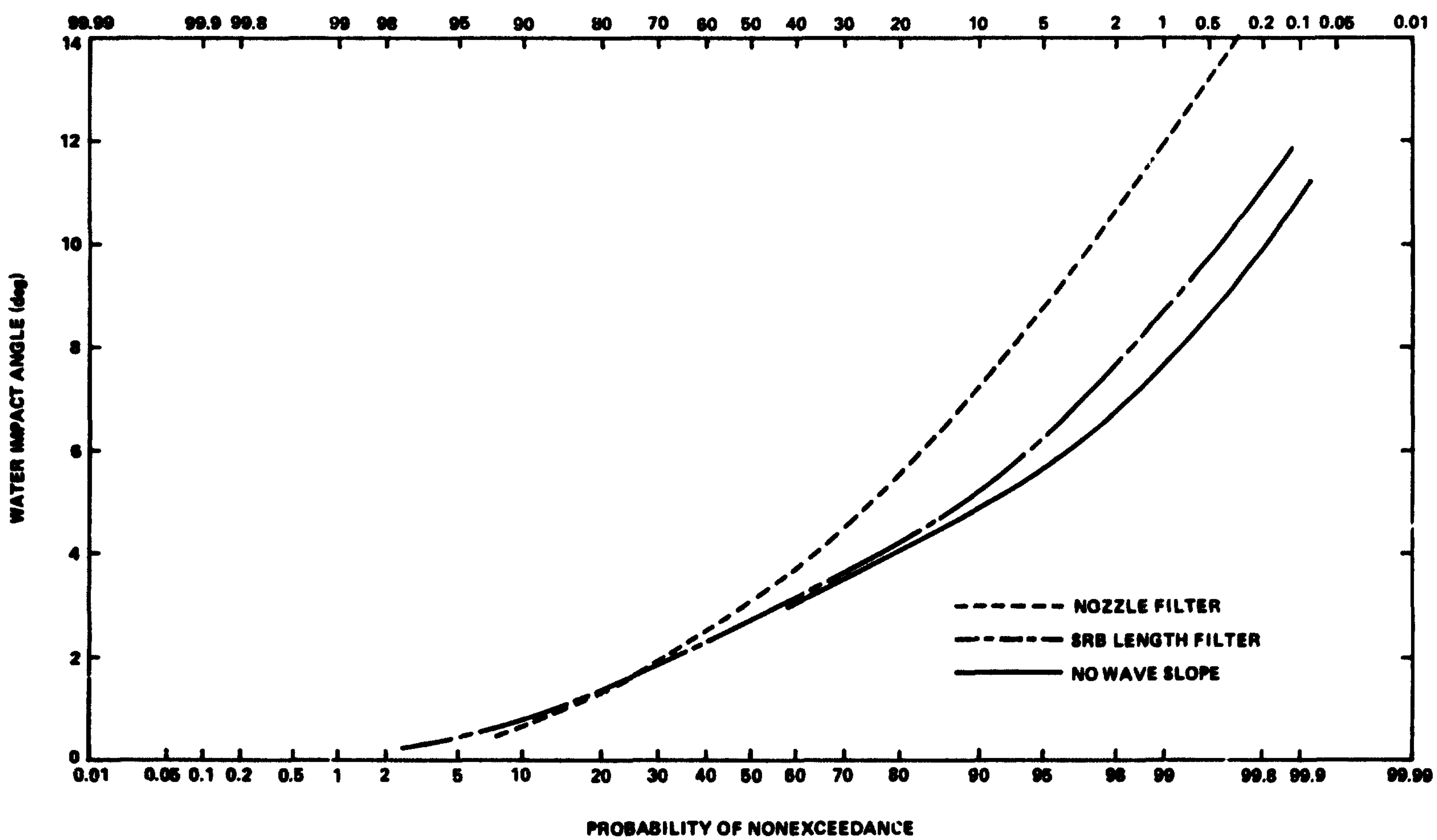


Figure 3. Water impact angle.

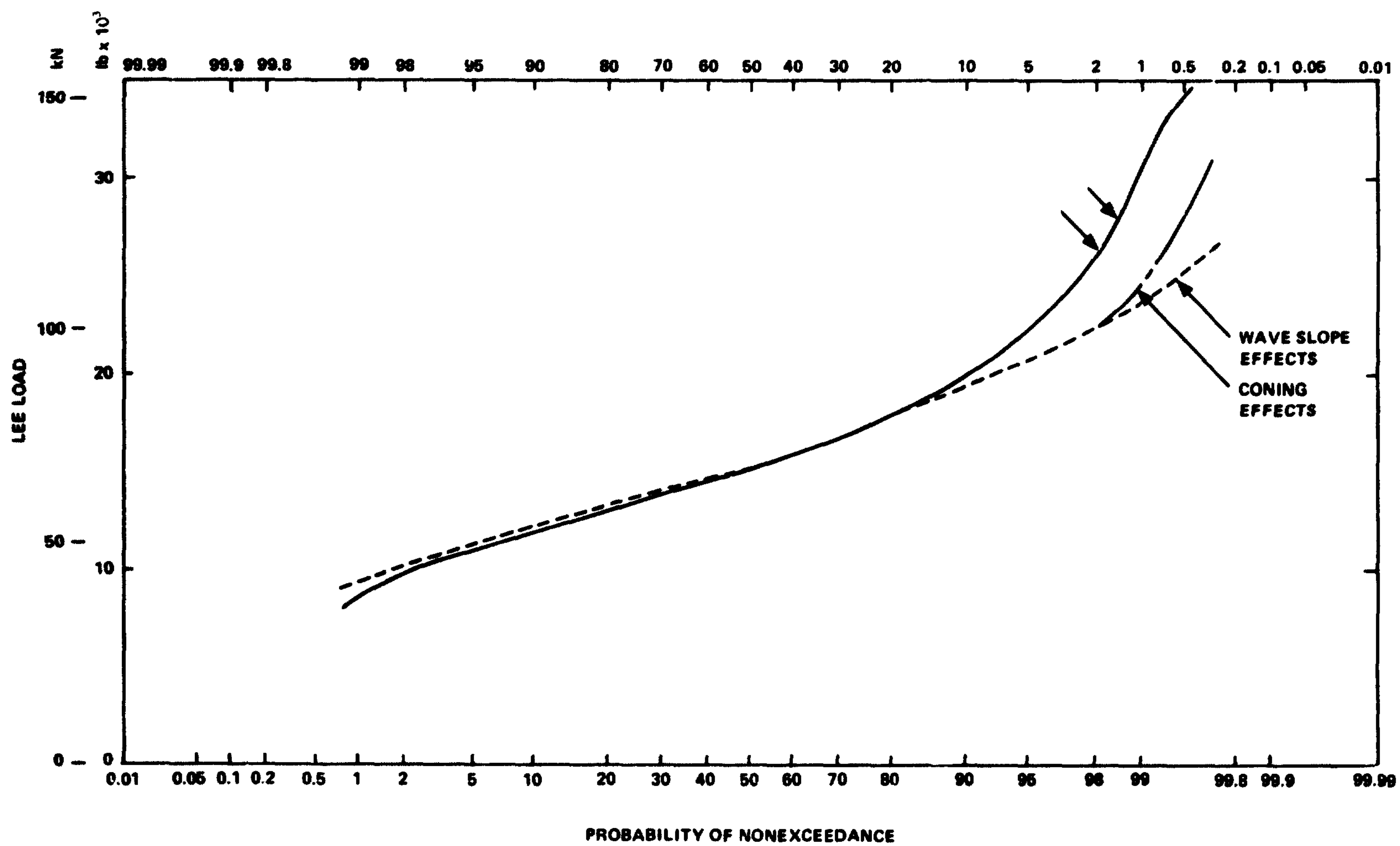


Figure 4. Wave slope and coning effects on cavity collapse load.

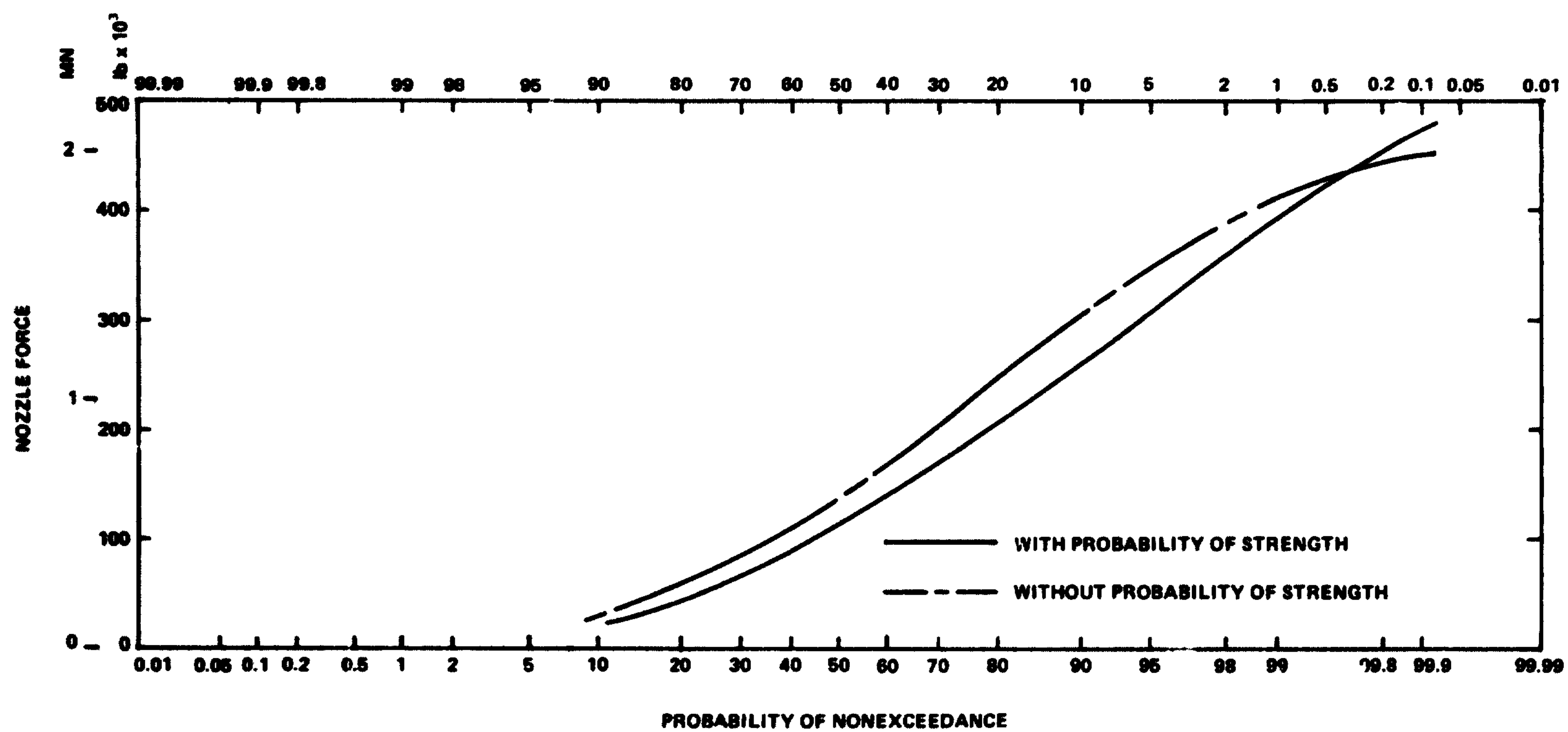


Figure 5. Nozzle side force, extension jettisoned.

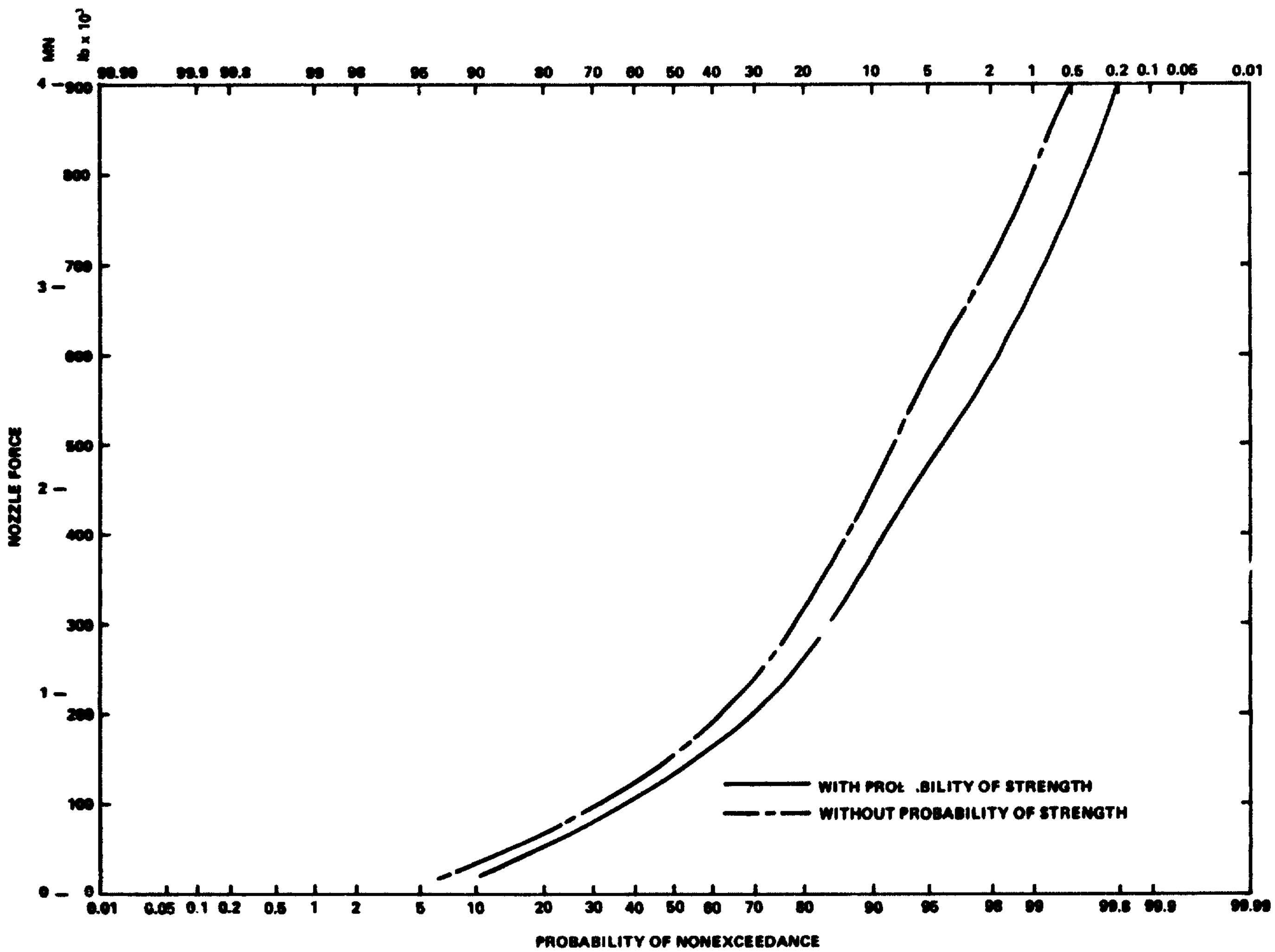


Figure 6. Nozzle side force, extension retained.

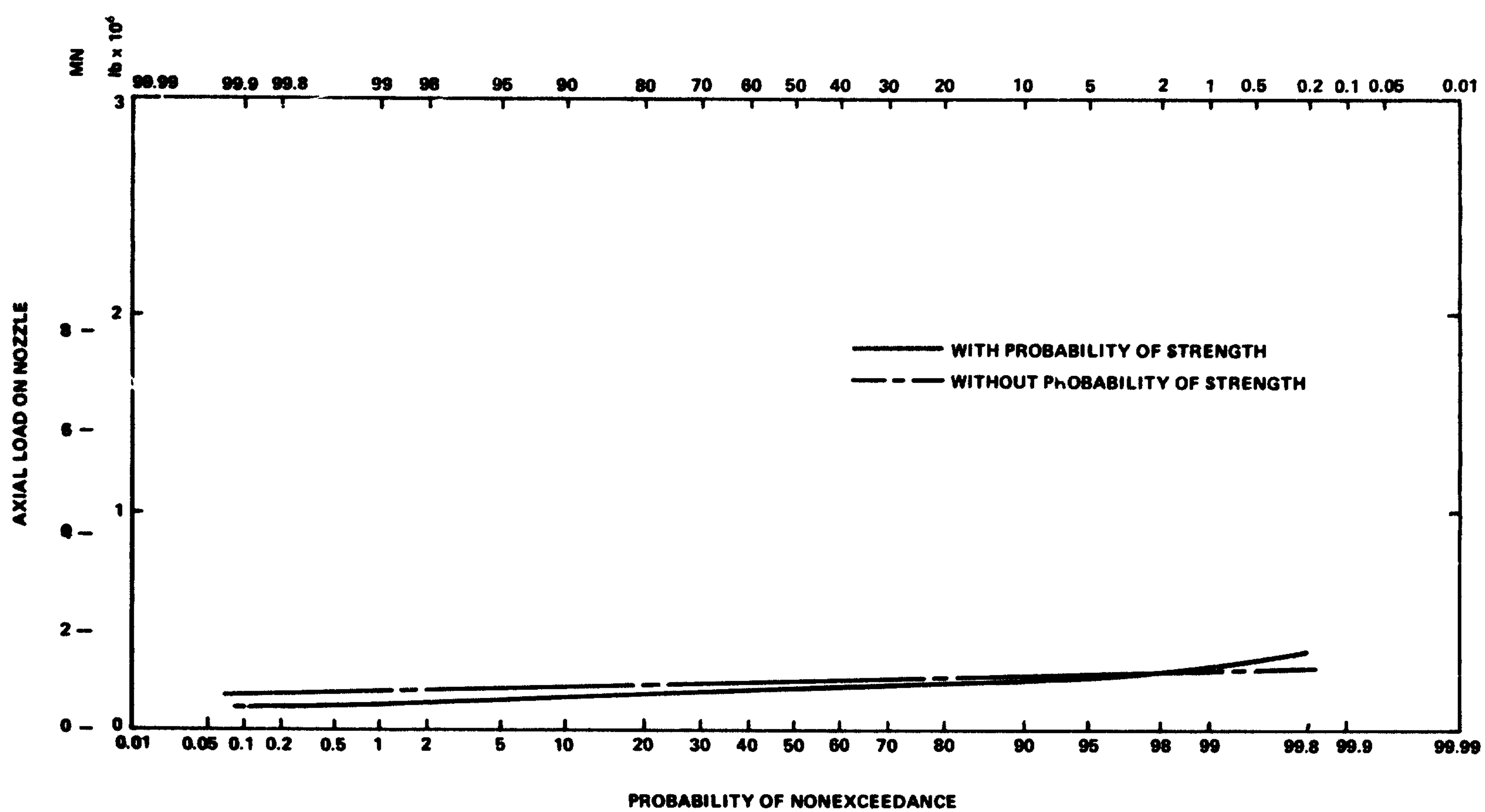


Figure 7. Nozzle axial force, extension jettisoned.

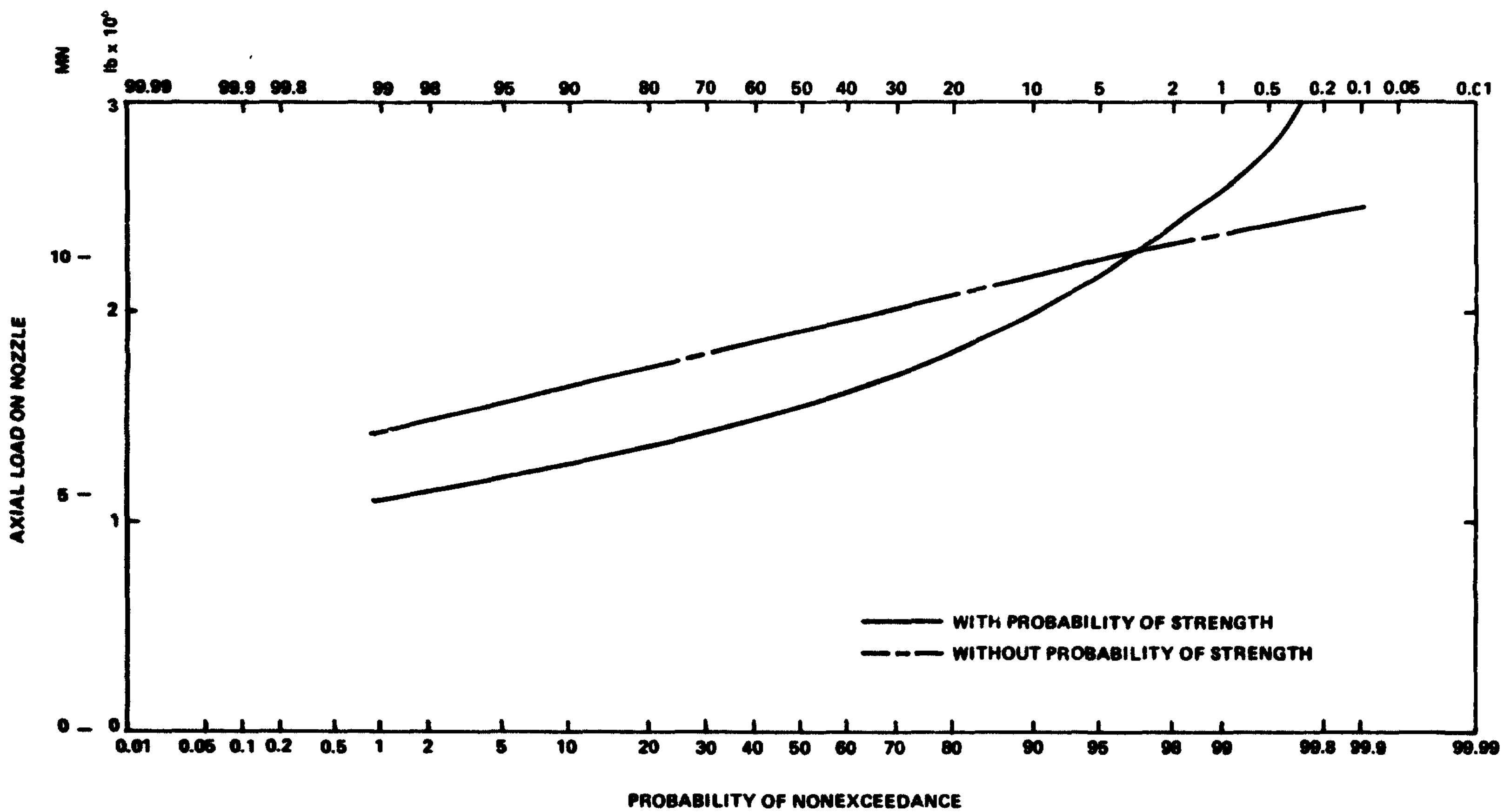


Figure 8. Nozzle axial load, extension retained.

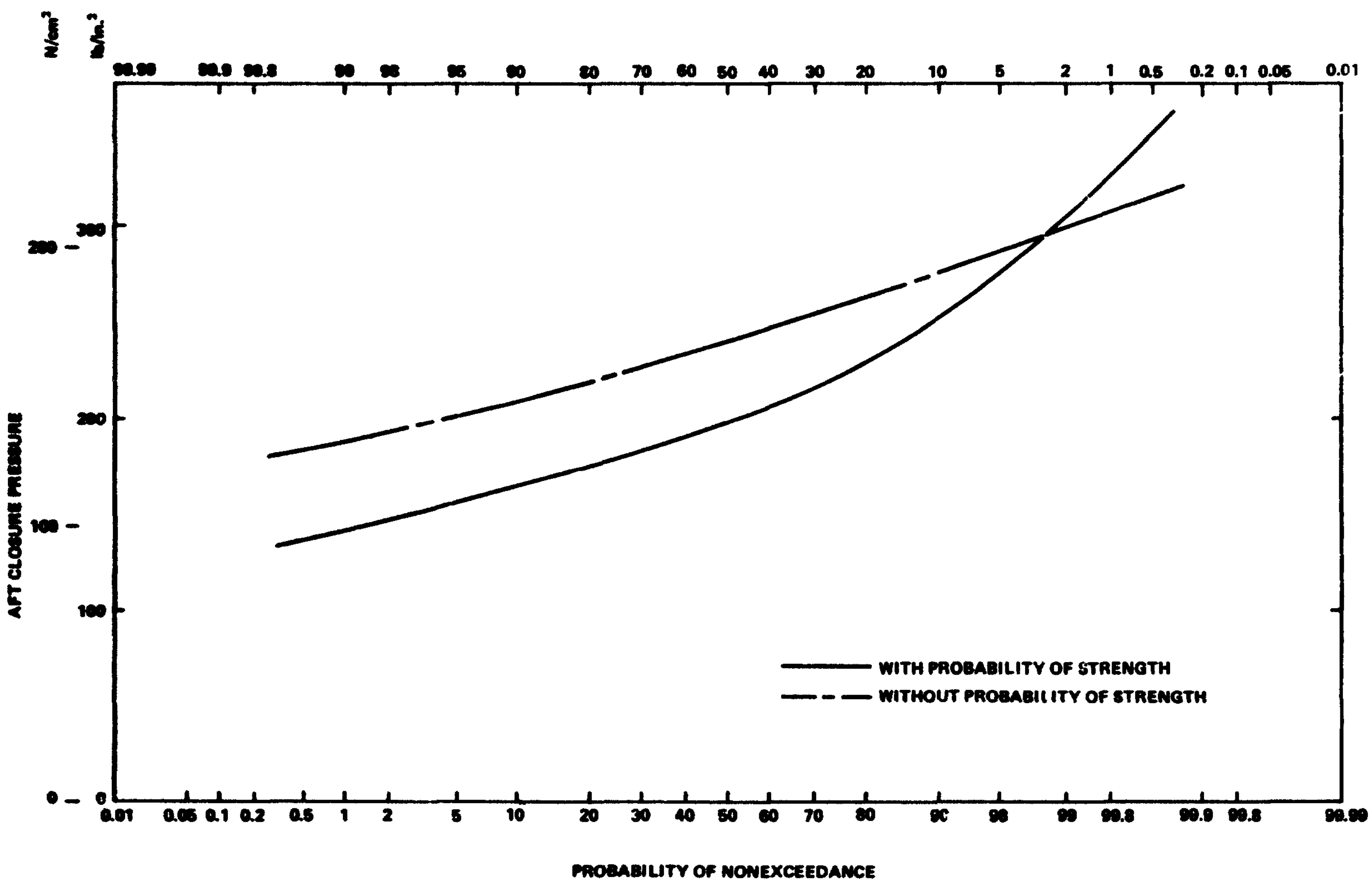


Figure 9. Aft closure pressure, extension jettisoned.

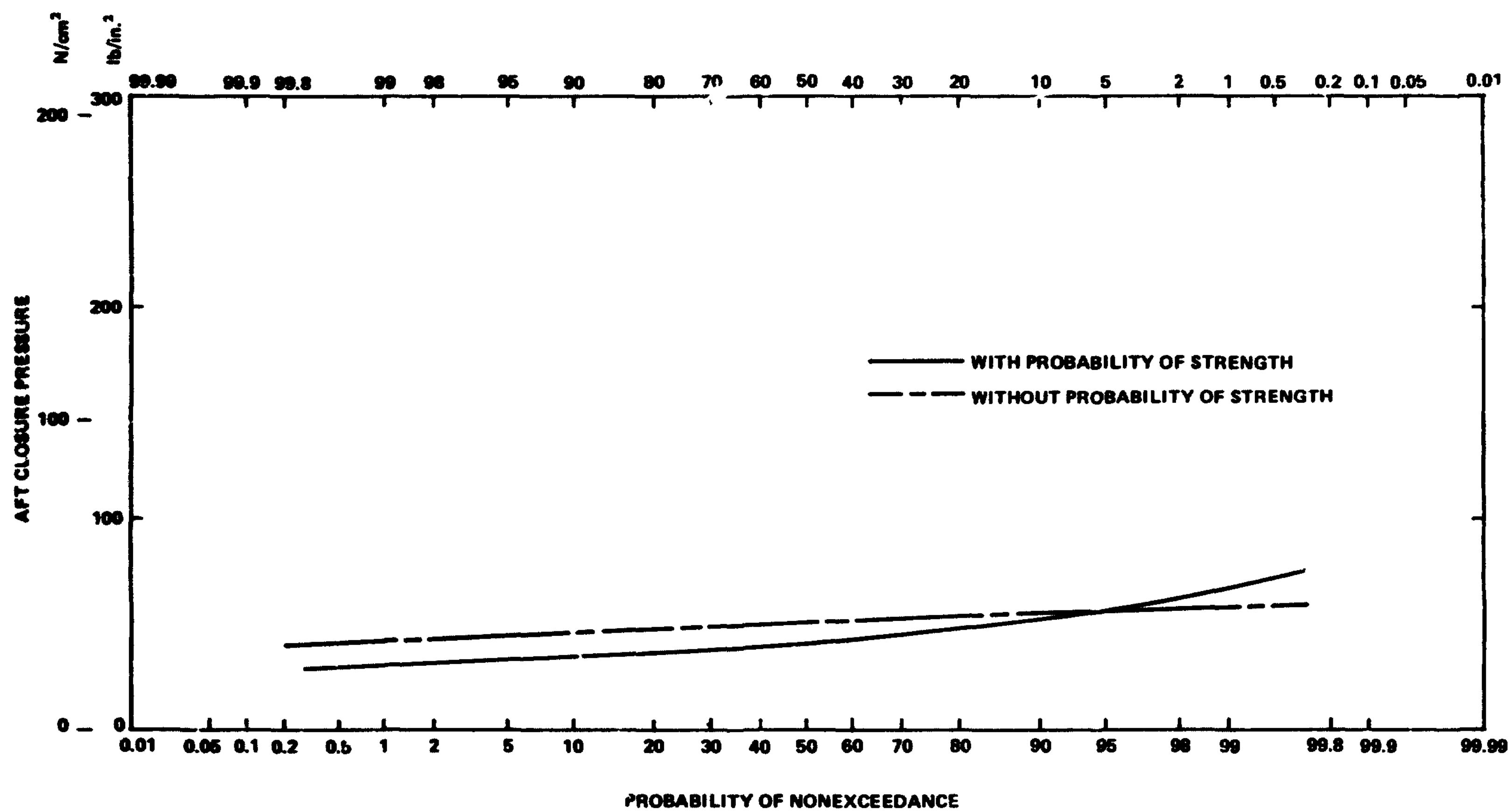


Figure 10. Aft closure pressure, extension retained.

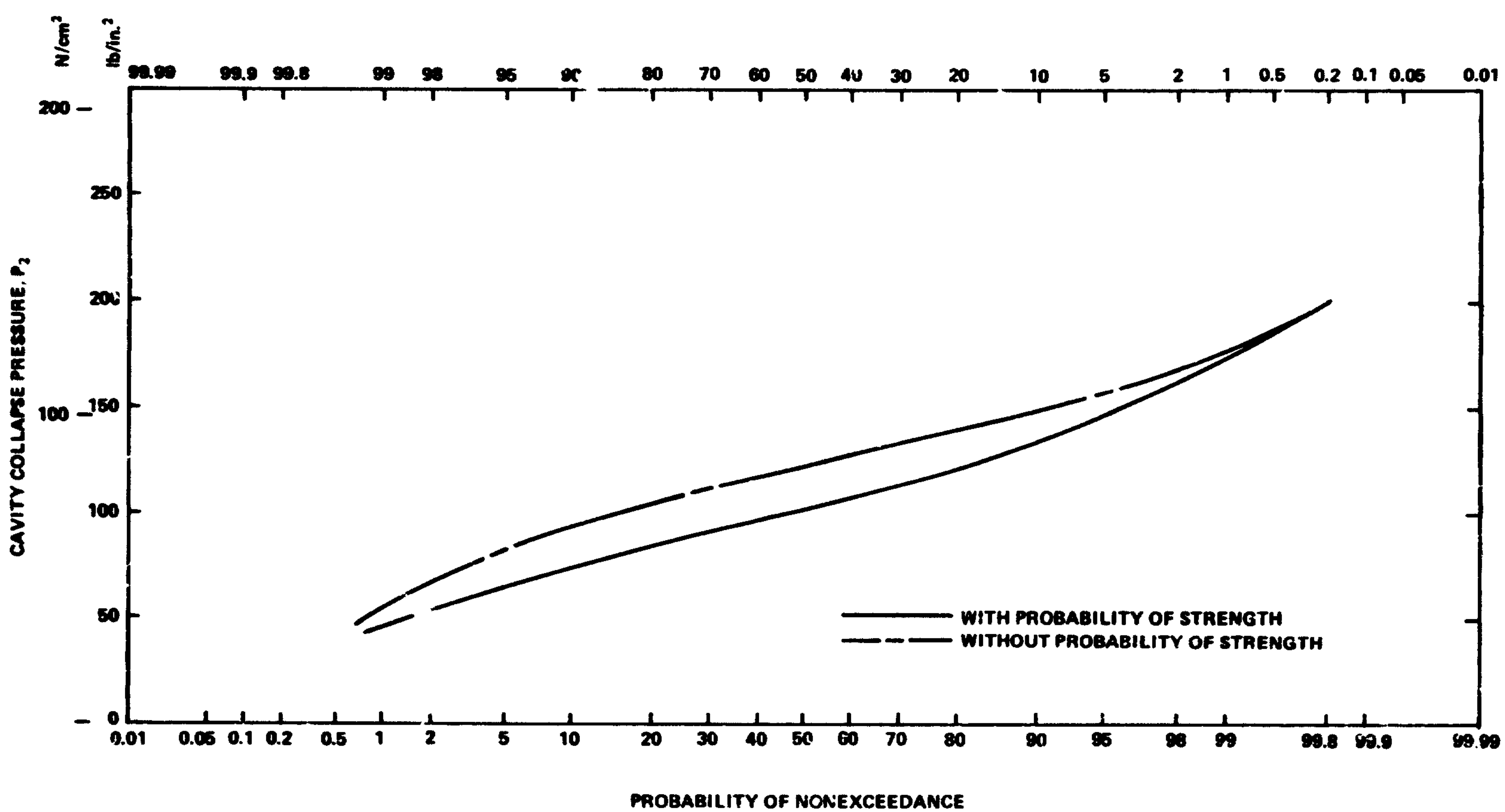


Figure 11. Cavity collapse pressure, extension jettisoned.

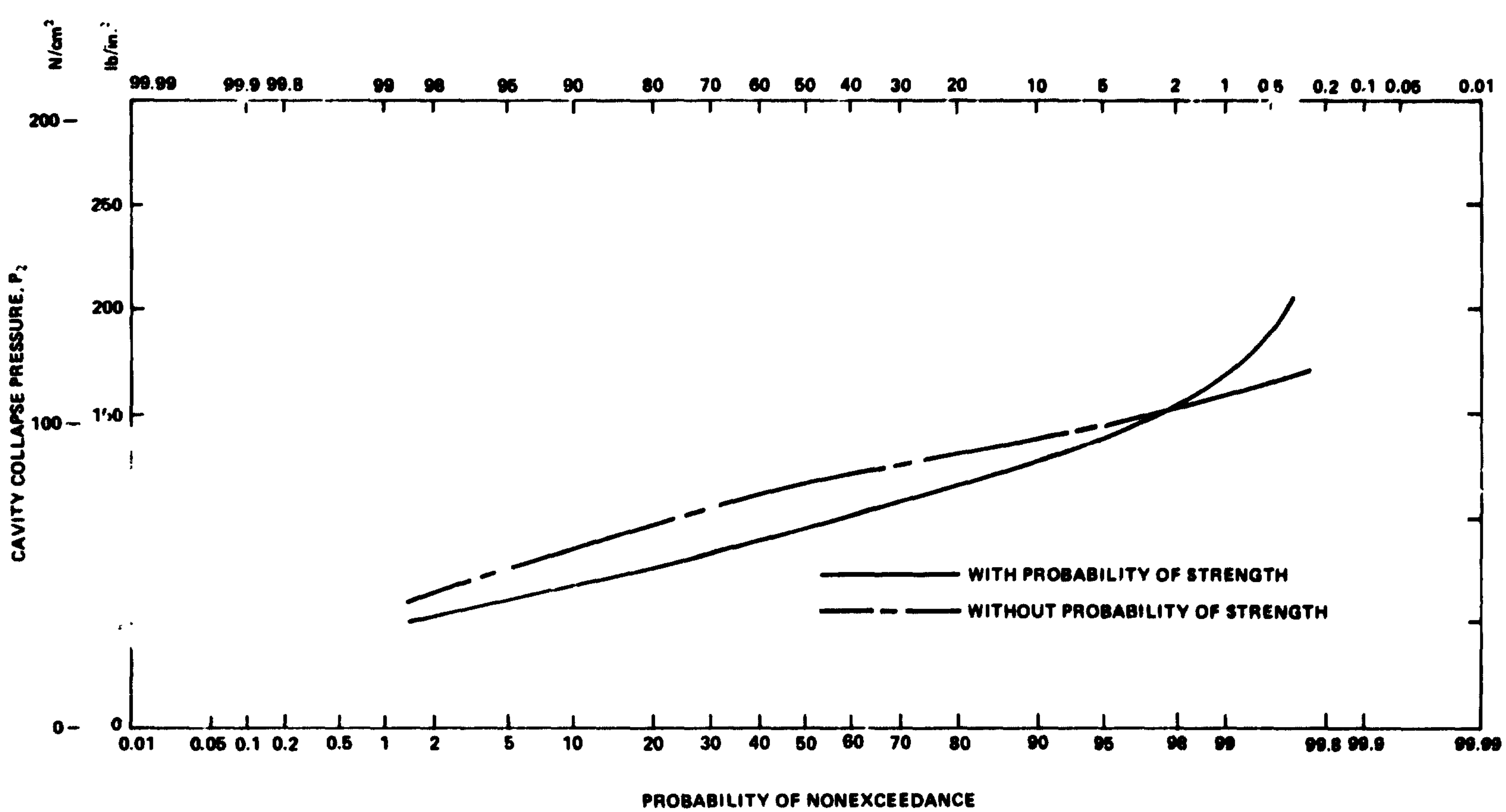


Figure 12. Cavity collapse pressure, extension retained.

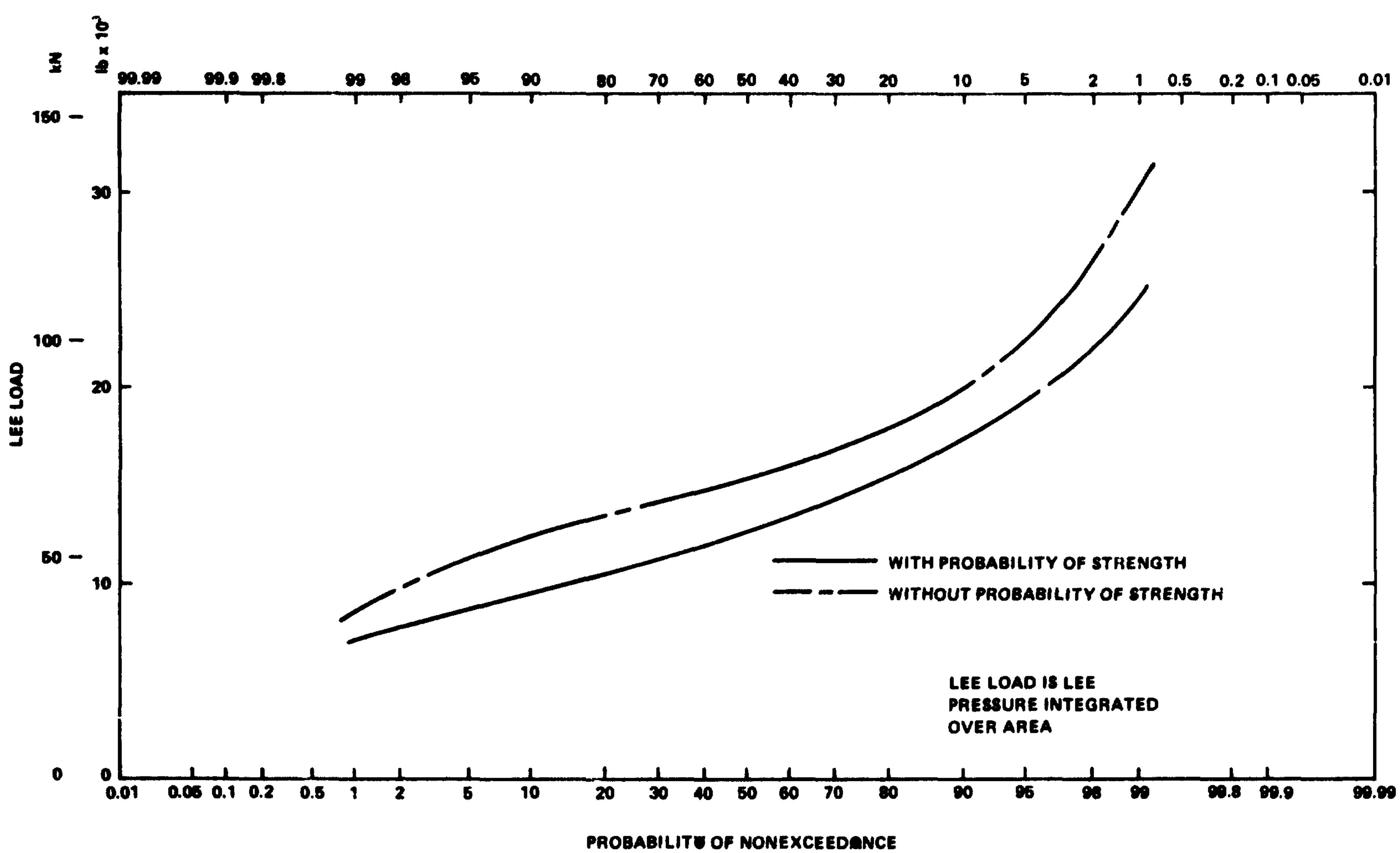


Figure 13. Cavity collapse load, extension jettisoned.

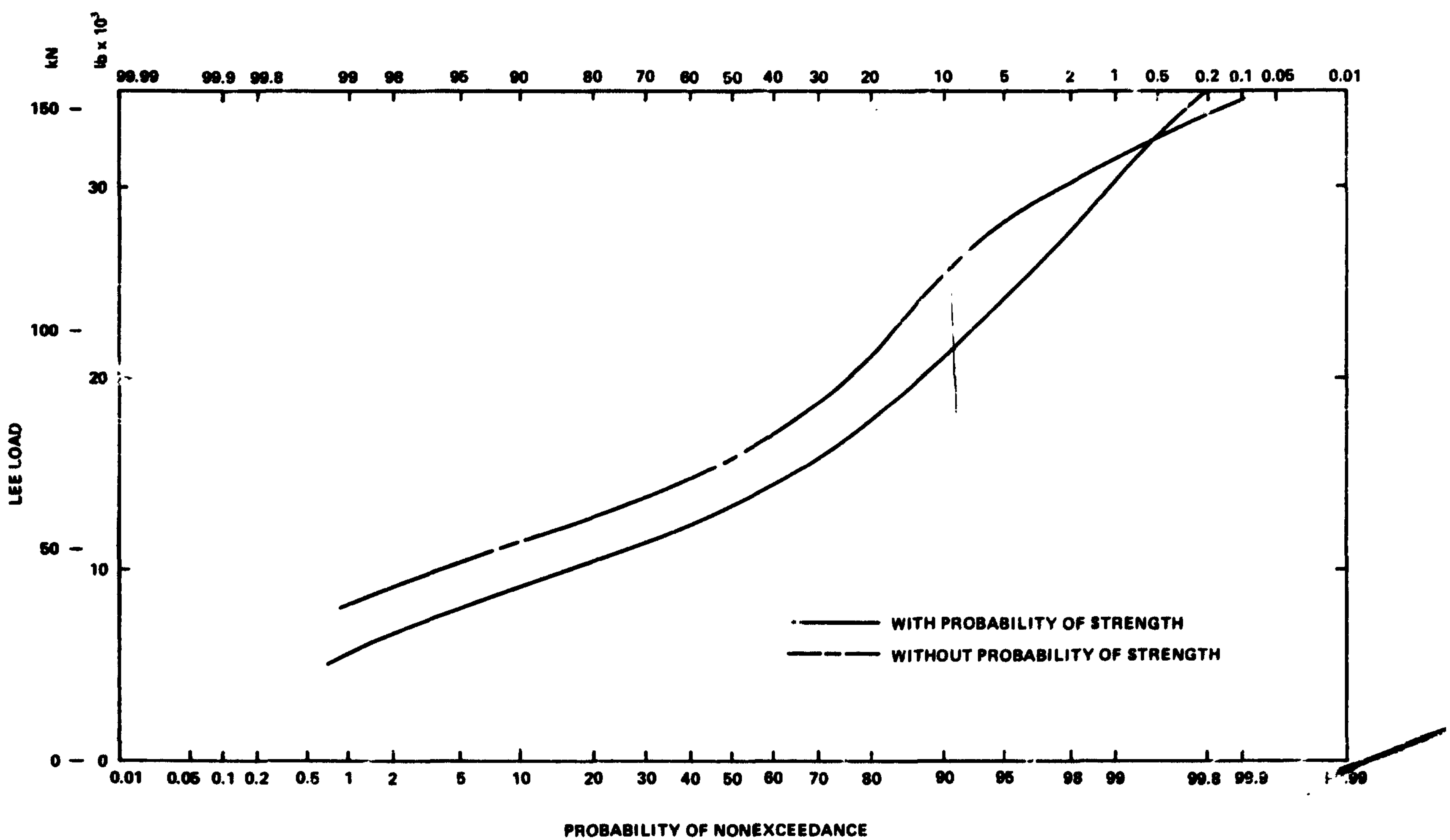


Figure 14. Cavity collapse load, extension retained.

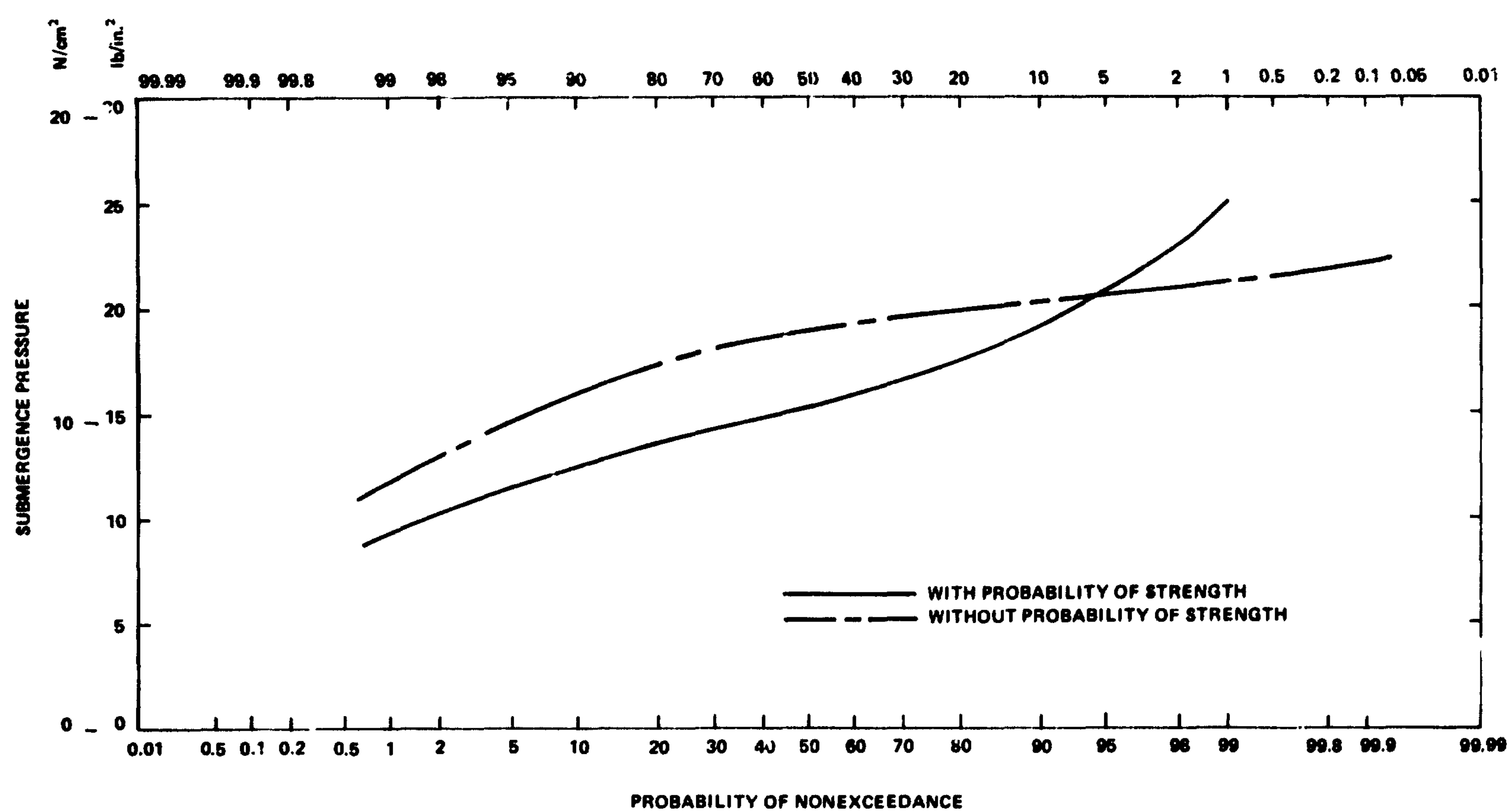


Figure 15. Submergence pressure, extension jettisoned.

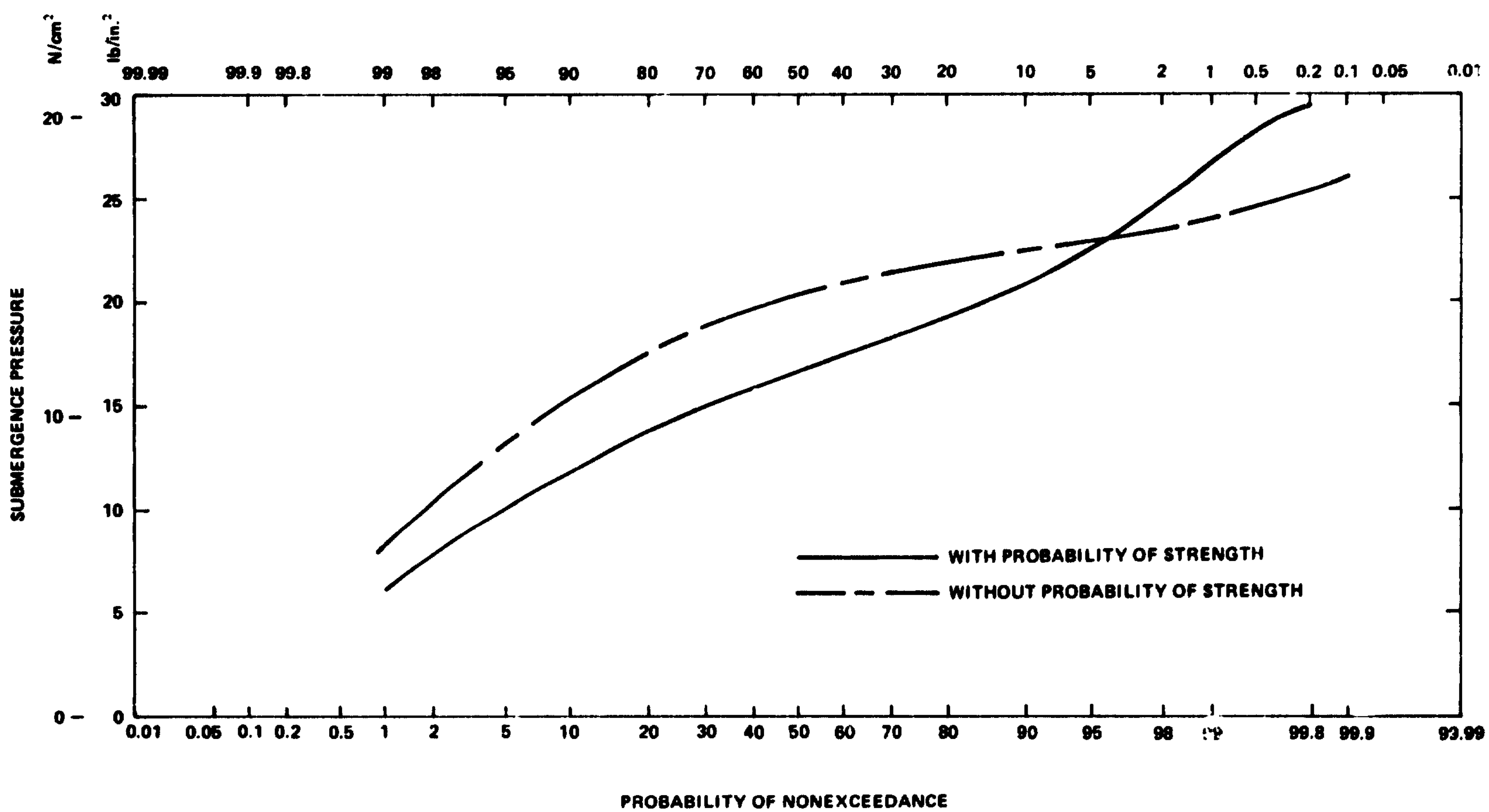


Figure 16. Submergence pressure, extension retained.

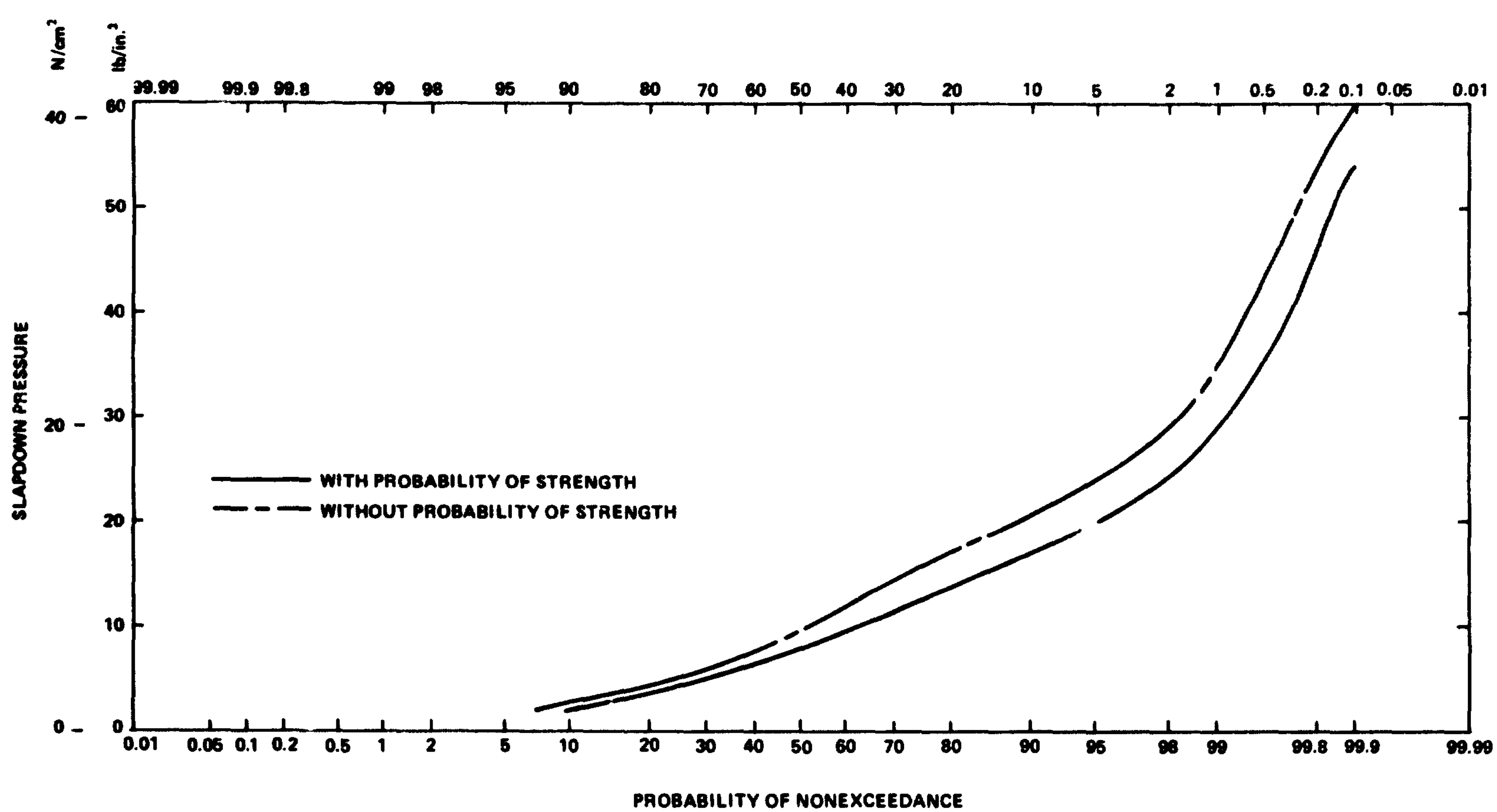


Figure 17. Slapdown pressure, extension jettisoned.

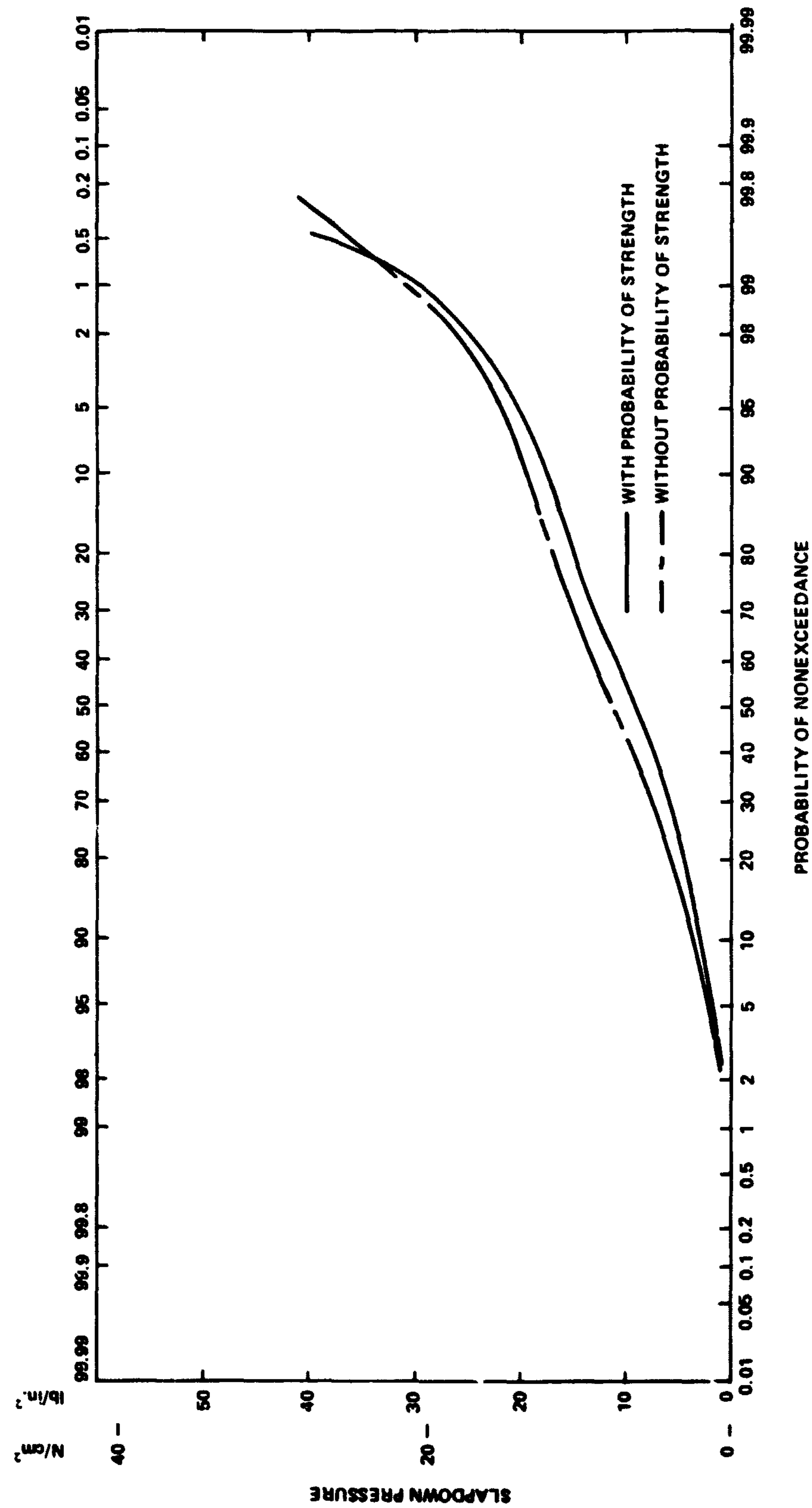
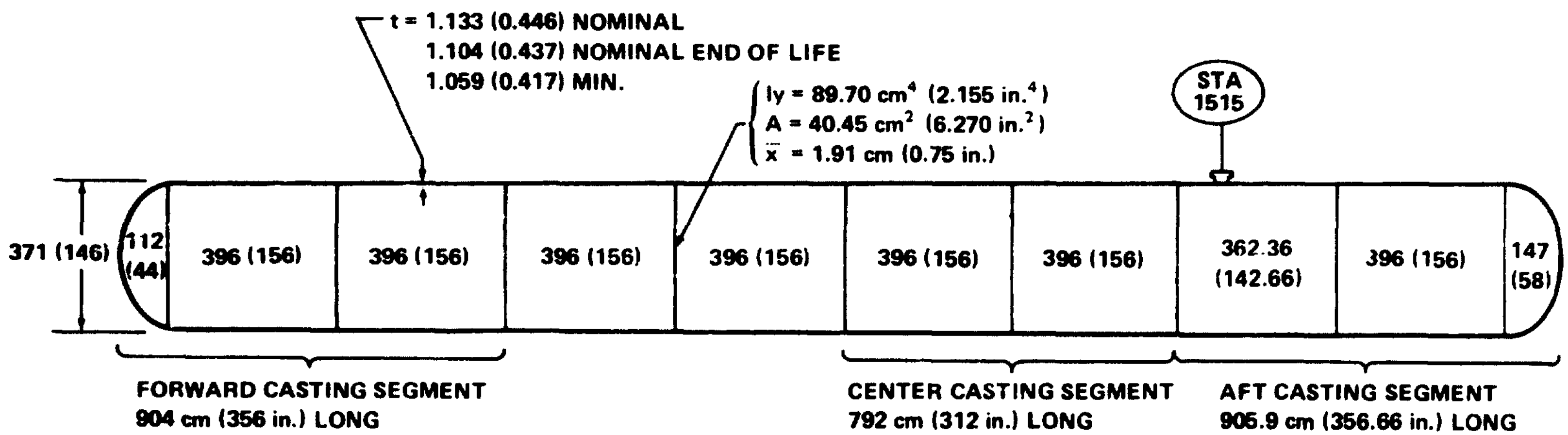


Figure 18. Slapdown pressure, extension retained.



UNITS: cm (in.)

MEOP = 570 N/cm² (827 PSIG)

Figure 19. Case segment configuration 0.

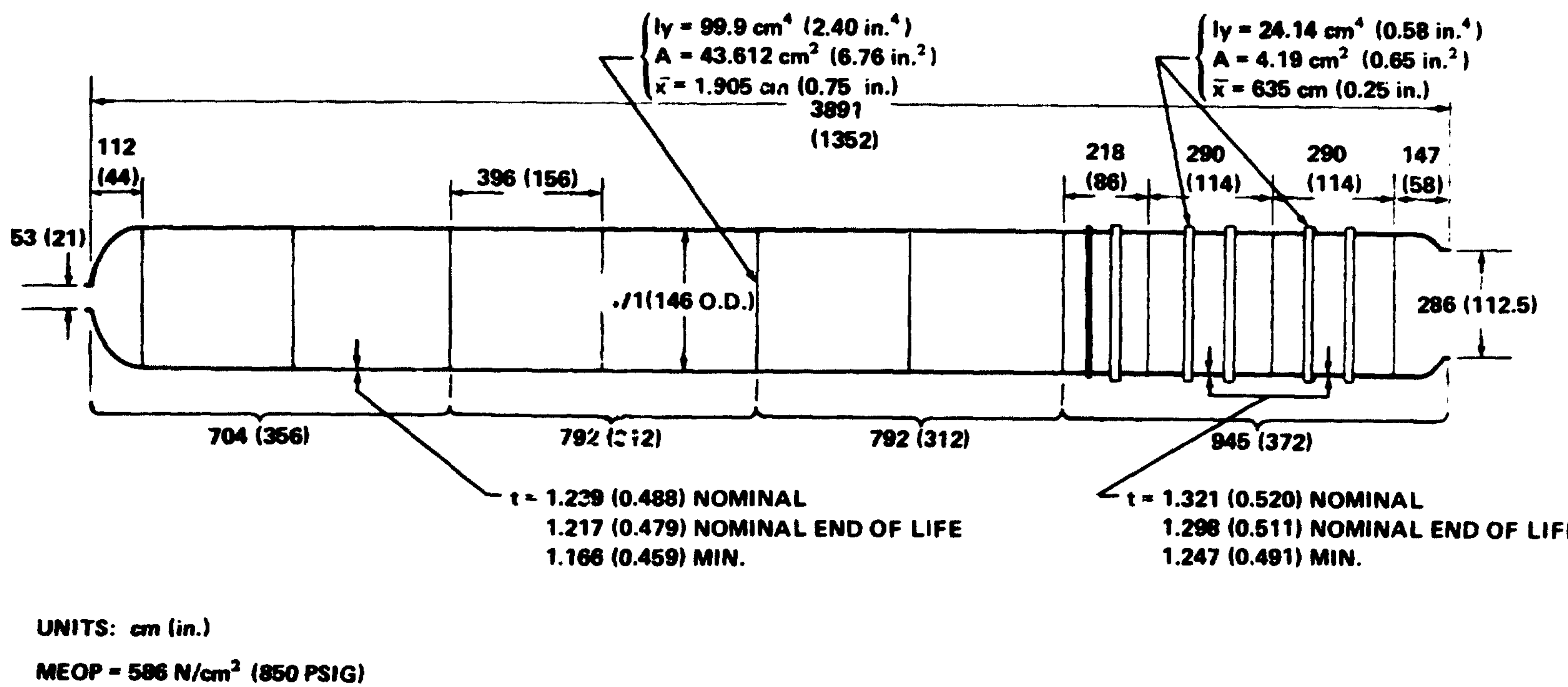


Figure 20. Case segment configuration 1.

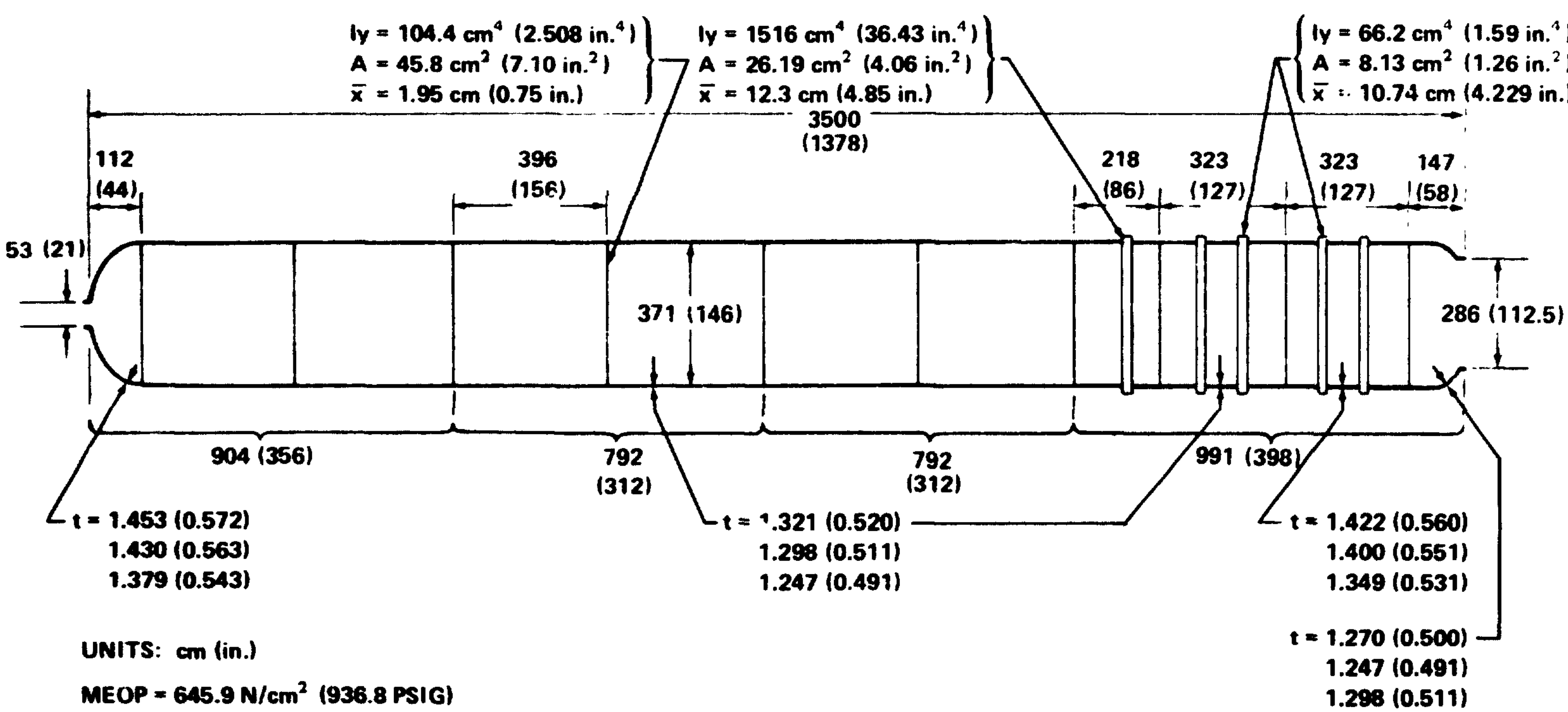
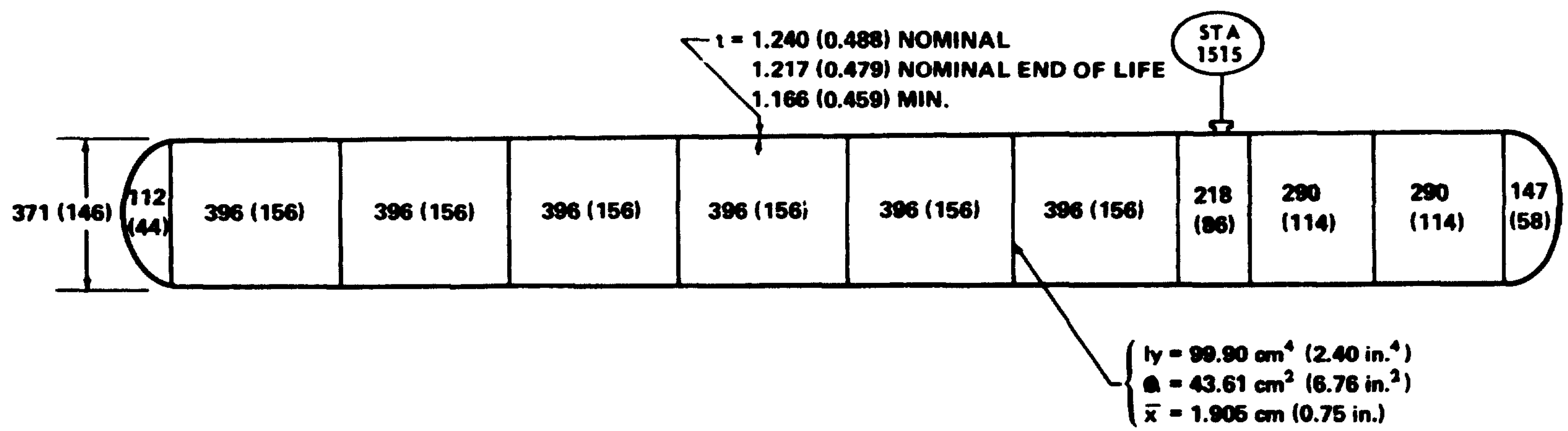


Figure 21. Case segment configuration 1-1 modified.



UNITS: cm (in.)

MEOP = 586 N/cm^2

Figure 22. Case segment configuration 3.

APPROVAL

SPLASH EVALUATION OF SRB DESIGNS

By Duane N. Counter

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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