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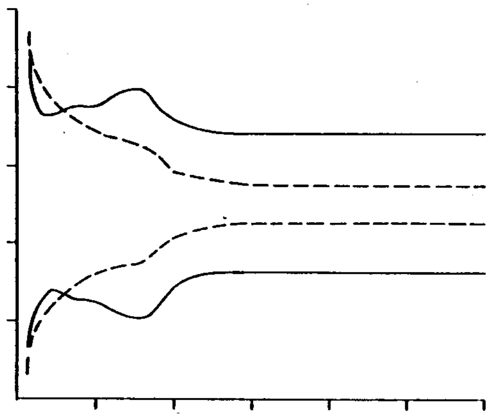
# OPTIMIZATION TECHNIQUES APPLIED TO PASSIVE MEASURES FOR IN-ORBIT SPACECRAFT SURVIVABILITY

## FINAL REPORT
(NAS8-37378)



Robert A. Mog
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November 1987

Prepared for George C. Marshall Space Flight Center,
Marshall Space Flight Center, AL 35812

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"OPTIMIZATION TECHNIQUES APPLIED TO PASSIVE MEASURES FOR IN-ORBIT SPACECRAFT SUVIVABILITY" IS A SIX-MONTH STUDY, DESIGNED TO EVALUATE THE EFFECTIVENESS OF THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE IN DETERMINING THE OPTIMAL DESIGN OF A METEOROID AND SPACE DEBRIS PROTECTION SYSTEM FOR THE SPACE STATION CORE MODULE CONFIGURATION. THE EFFORT IS DIRECTED BY SHERMAN L. AVANS, ED52.

THE AUTHORS WISH TO THANK MR. AVANS FOR HIS OVERALL DIRECTION AND "REAL WORLD" INPUTS ON THIS STUDY. WE ALSO WANT TO THANK MS. JENNIFER HORN FOR PROVIDING DIRECTION ON THE DESIGN TRADES THAT WERE PERFORMED AS WELL AS MANY OF THE REFERENCES AND BASELINE PARAMETERS.

THE AUTHORS ALSO WISH TO THANK FRANCES CHEEK OF SAIC FOR HER CONSULTATIONS AND QUALITY REVIEW OF THIS REPORT.

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# MOTIVATION

- MANY FUNCTIONAL IMPACT PREDICTORS/MODELS ARE AVAILABLE
- MODELS ARE SOMETIMES CONFLICTING/CONFUSING
- MODELS ARE OFTEN NOT WELL-DOCUMENTED
- MODELS HAVE DIFFERENT PARAMETER SPACES AND DIFFERENT ORIGINS/ASSUMPTIONS
- FUNCTIONAL PREDICTORS ARE SUPERIOR TO NON-ANALYTICAL MODELS FOR DESIGNER TRADE-OFF STUDIES

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# HOW THIS STUDY COMPLEMENTS OTHER EFFORTS

- PROVIDES A TOOL FOR DISSECTING THE MASS OF IMPACT PREDICTORS/ MODELS AVAILABLE TO THE DESIGNER
- ESTABLISHES OPTIMAL DESIGN DATA BASED ON THE CURRENT PREDICTORS FOR COMPARISON WITH TESTING
- COMPLEMENTS BOEING'S EFFORTS WITH A HOST OF PERTINENT DESIGN TRADEOFFS
- ESTABLISHES A DATA BASE OF PREDICTOR ATTRIBUTES

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## WHAT YOU WILL SEE

- A DISCUSSION OF OPTIMIZATION TECHNIQUES
- SIGNIFICANT DESIGN TRADES FOR SEVERAL PREDICTORS UNDER DIFFERENT ASSUMPTIONS
- AN ASSESSMENT OF GEOMETRIC PROGRAMMING

## WHAT YOU WON'T SEE

- THE DEVELOPMENT OF NEW PREDICTORS
- THE NOMINATION OF A PREDICTOR
- A RECOMMENDED CORE MODULE DESIGN
- CONSIDERATION OF MLI, SUPPORT STRUCTURE, OR OTHER DESIGN ACCOUNTS (STRESS, THERMAL, ETC.)



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# CONTENTS



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# TERMINOLOGY

**WALL** - THE CORE MODULE PRESSURE SURFACE OR STRUCTURE

**BUMPER** - A SHIELD OR PLATE SPACED OUTBOARD FROM THE WALL

**OPTIMAL RATIO** - THE THICKNESS DISTRIBUTION (IN PERCENT) BETWEEN THE BUMPER AND WALL THAT OPTIMIZES THE DESIGN OBJECTIVE

**"WEIGHT"** - THE SUM OF THE BUMPER AND WALL THICKNESSES

**WEIGHT** - THE THEORETICAL DRY CORE MODULE EARTH-MASS AS ATTRIBUTED TO THE BUMPER AND WALL THICKNESSES AND MODULE CONFIGURATION.

**MISSION RISK** - ONE MINUS THE PROBABILITY OF NO PENETRATION

**INDEPENDENT VARIABLE(S)** - THE PARAMETER(S) THAT ARE CONTROLLABLE IN SOME SENSE BY THE SYSTEM DESIGNER

**GLOBAL** - A FORM OF OPTIMIZATION THAT RESULTS IN THE OVERALL OR COMPREHENSIVE BEST SOLUTION

**LOCAL** - A FORM OF OPTIMIZATION THAT RESULTS IN THE BEST SOLUTION FOR SOME NEIGHBORHOOD OF THE INDEPENDENT VARIABLE

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# TERMINOLOGY (CONTINUED)

<u>FUNCTIONAL</u> - A MATHEMATICAL RELATIONSHIP THAT MAY BE WRITTEN EXPLICITLY

<u>PREDICTOR</u> - A MODEL, EITHER FUNCTIONAL OR NON-ANALYTICAL, WHICH DESCRIBES THE IMPACT PHYSICS (E.G., NYSMITH, WILKINSON, BURCH, MODIFIED BURCH, PEN4, BOEING, MADDEN, RICHARDSON)

<u>NONLINEAR</u> - A PREDICTOR WHOSE INDEPENDENT VARIABLES HAVE EXPONENTS THAT ARE NOT ALL EQUAL TO UNITY

<u>DEGREE-OF-DIFFICULTY</u> - IN AN OPTIMIZATION TECHNIQUE, THE NUMBER OF VARIABLES THAT MUST BE SOLVED FOR MINUS THE NUMBER OF INDEPENDENT EQUATIONS AVAILABLE

<u>CONSTRAINT</u> - AN EQUATION OR INEQUALITY WHICH LIMITS THE USAGE OF A PREDICTOR

<u>POSYNOMIAL</u> - A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND WHOSE INDEPENDENT VARIABLES ARE POSITIVE-VALUED

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# TERMINOLOGY (CONTINUED)

**PARAMETER SPACE** - THE TOTAL NUMBER OF POSSIBLE INDEPENDENT VARIABLES ASSOCIATED WITH A PREDICTOR

**IDEALIZED SCENARIO** - AN IMPACT SCENARIO SIMILAR TO A TEST SETUP AND CHARACTERIZED BY FLAT PLATES MODELLING THE BUMPER AND WALL AND NO SUPPORT STRUCTURE

**OBJECTIVE FUNCTION** - THE EQUATION OR FUNCTION WHICH CHARACTERIZES THE OPTIMIZATION GOAL OF THE SYSTEM DESIGNER

**INFLECTION** - A POINT IN A DESIGN TRADEOFF CURVE AT WHICH THE SLOPE CHANGES FROM DECREASING TO INCREASING, OR VICE VERSA

**PIECEWISE CONTINUOUS** - A SET OF EQUATIONS, EACH OF WHICH IS CONTINUOUS, BUT WHEN COMBINED, MAY BE DISCONTINUOUS AT A FINITE NUMBER OF POINTS (E.G., WILKINSON, BOEING PREDICTORS)

**MONOTONIC** - STRICTLY INCREASING, DECREASING, OR CONSTANT

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# SECTION I

## OPTIMIZATION TECHNIQUES BACKGROUND AND COMPARISON

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# WHAT YOU WILL SEE IN SECTION I

- PROTECTIVE SYSTEMS DESIGN OPTIMIZATION PROBLEM FORMULATION
- DISCUSSION OF SPECIFIC OPTIMIZATION TECHNIQUE ATTRIBUTES
- EXAMPLE APPLICATION



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# WHAT OPTIMIZATION MEANS IN THIS STUDY

FINDING THOSE DESIGN THICKNESSES WHICH PROVIDE THE GREATEST PROTECTIVE CAPABILITY (WITH RESPECT TO THE METEOROID AND SPACE DEBRIS ENVIRONS) WHILE INDUCING THE LEAST WEIGHT, AND THUS COST.

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# WHY THIS DESIGN OPTIMIZATION IS IMPORTANT

- METEOROID AND SPACE DEBRIS ENVIRONS OFTEN DRIVE STRUCTURAL DESIGN
- SAFETY IS A HIGH PRIORITY
- DESIGN FEASIBILITY IS AT STAKE
- THE ENVIRONMENT IS NOT STATIC
- POLICY IS SIGNIFICANTLY AFFECTED BY COST
- IMPACT SCIENCE IS YOUNG

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## PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

THE BASIC PARAMETERS ASSOCIATED WITH DESIGN OF THE PROTECTIVE SYSTEMS FOR SPACECRAFT WHICH MUST ENDURE THE THREAT OF METEOROIDS AND SPACE DEBRIS MAY BE CATEGORIZED AS MISSION PARAMETERS AND DESIGN PARAMETERS. TYPICALLY, MISSION PARAMETERS SUCH AS ORBIT, ACCEPTABLE MISSION RISK, MISSION DURATION, AND SPACECRAFT SIZE ARE USED TO DETERMINE THE DESIGN PROJECTILE MASS AND DIAMETER. THE PROJECTILE VELOCITY IS THEN CONSIDERED TO COMPLETE THE SET OF THREAT CHARACTERISTICS. DESIGN PARAMETERS SUCH AS BUMPER/WALL THICKNESS, DENSITIES, AREAS, AND SEPARATION ARE USED TO ASSESS THE EFFECTIVENESS OF THE DESIGN IN RESISTING PROJECTILE PENETRATION.

THE SYSTEM DESIGNER'S ROLE IS TO CREATE OR CHOOSE A RELATIONSHIP BETWEEN THE REQUIRED DESIGN PARAMETERS AND THE MISSION AND THREAT PARAMETERS. THE DESIGNER MUST THEN OPTIMIZE AN OBJECTIVE FUNCTION COMPOSED OF THE DESIGN PARAMETERS, E.G., WEIGHT.

# PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

- **PARAMETERS**
  - **MISSION (THREAT):** PROJECTILE CHARACTERISTICS — DETERMINED FROM ORBIT (DEFINES ENVIRONMENT), ACCEPTABLE LEVEL OF RISK FOR MISSION, MISSION DURATION, SPACECRAFT SIZE
  - **DESIGN:** CONFIGURATION-SPECIFIC PARAMETERS OF PROTECTIVE SYSTEMS (e.g., thicknesses, densities, dimensions)
- **THE SYSTEM DESIGNER's ROLE**
  - DETERMINE THE DESIGN PARAMETERS BASED ON THE MISSION PARAMETERS
  - OPTIMIZE A SPECIFIC FUNCTION OF THESE DESIGN PARAMETERS

# CLASSICAL APPROACHES

IMPACT PREDICTORS MAY BE CLASSIFIED AS FUNCTIONAL OR NON-ANALYTICAL. AMONG FUNCTIONAL PREDICTORS, ONE HAS THEORETICAL (E.G., MADDEN EQUATION) AND EXPERIMENTAL (E.G., NYSMITH EQUATION) MODELS. NON-ANALYTICAL MODELS SUCH AS THE HULL CODE TYPICALLY ARE NUMERICAL TECHNIQUES EMPLOYING PARTIAL DIFFERENTIAL EQUATIONS TO SOLVE THE EQUATIONS OF SOLID AND FLUID MECHANICS.

THE FIRST STEP IN THE OPTIMIZATION PROCESS IS TO DEVELOP THE OBJECTIVE FUNCTION(S) IN TERMS OF FUNCTIONAL PREDICTOR(S). TYPICAL FUNCTIONS DESCRIBE LAUNCH WEIGHT OR COST ASSOCIATED WITH PROTECTIVE SYSTEMS.

# CLASSICAL APPROACHES

- **PREDICTORS RELATE MISSION TO DESIGN PARAMETERS**
  - FUNCTIONAL: THEORETICAL VS EXPERIMENTAL (e.g., Nysmith Equation)
  - NON-ANALYTICAL (e.g., HULL Code)
- **OPTIMIZATION FUNCTIONS COMPOSED OF FUNCTIONAL PREDICTORS**
  - FUNCTIONS DESCRIBING LAUNCH WEIGHT ASSOCIATED WITH PROTECTIVE SYSTEMS
  - FUNCTIONS DESCRIBING COST ESTIMATING RELATIONSHIPS ASSOCIATED WITH PROTECTIVE SYSTEMS

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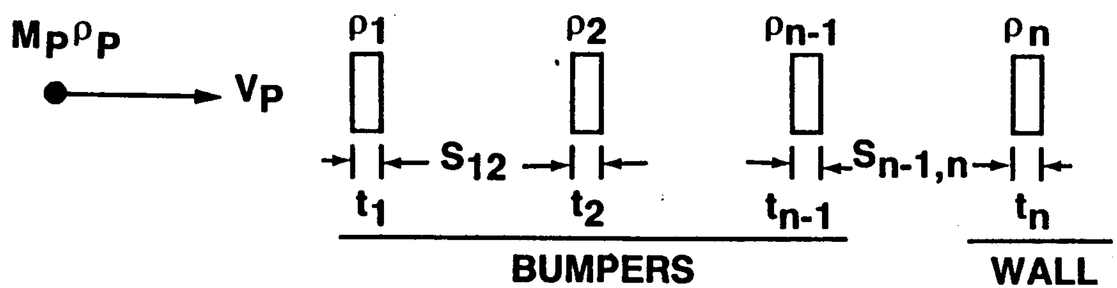
# IDEALIZED SPACECRAFT IMPACT SCENARIO

FOR ANALYSIS PURPOSES, AN IDEALIZED SCENARIO WAS DEVELOPED AS A BASIS TO COMPARE VARIOUS PREDICTORS.

THIS IDEALIZED SCENARIO IS SHOWN FOR A FAIRLY COMPLETE SET OF DESIGN AND PROJECTILE CHARACTERISTICS. THE "WEIGHT" FUNCTION ASSUMED IS THE PRODUCT OF THE PLATE DENSITY AND PLATE THICKNESS SUMMED OVER THE TOTAL NUMBER OF PLATES. AS WE SHALL SEE, FOR THE NYSMITH PREDICTOR, THERE IS ONLY ONE BUMPER AND ONE WALL. FURTHERMORE, THE NYSMITH PREDICTOR SHOWS NO DEPENDENCE ON BUMPER/WALL DENSITIES. THEREFORE, THE BUMPER THICKNESS IS THE INDEPENDENT VARIABLE, AND THE "WEIGHT" FUNCTION IS SUFFICIENTLY EXPRESSED AS THE SUM OF THE BUMPER AND WALL THICKNESSES.

# IDEALIZED SPACECRAFT IMPACT SCENARIO




| | | |
|---|---|---|
| $M_P$ | = | mass of projectile |
| $\rho_P$ | = | density of projectile |
| $V_P$ | = | velocity of projectile |
| $t_i$ | = | bumper thickness, $i=1, 2, \ldots, n-1$, |
| $t_n$ | = | wall thickness, |
| $\rho_i$ | = | bumper density, $i = 1, 2, \ldots, n-1$, |
| $\rho_n$ | = | wall density |
| $S_{i,\,i+1}$ | = | distance between bumper i and bumper i+1. |

"WEIGHT" FUNCTION:

$$W_T = \sum_{i=1}^{n} \rho_i t_i \quad \text{for constant normal plate areas.}$$

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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

THE TRADITIONAL APPROACH TO CONTINUOUS AND OFTEN NONLINEAR FUNCTIONAL OPTIMIZATION HAS BEEN TO APPLY EXTREMA THEOREMS FROM THE CALCULUS. HOWEVER, THIS APPROACH ONLY PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA. THUS, THIS TECHNIQUE MAY FAIL IN TWO ENTIRELY DIFFERENT WAYS. IT MAY FAIL TO LOCATE CERTAIN EXTREMA, AND IF IT DOES LOCATE AN EXTREMA POINT FOR THE PROBLEM, THERE IS NO GUARANTEE THAT IT IS A GLOBAL EXTREMA. FURTHERMORE, THIS METHOD REQUIRES THE EVALUATION OF PARTIAL DERIVATIVES AND HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS INCLUDED IN THE PROBLEM FORMULATION. FINALLY, THIS METHOD IS CUMBERSOME FOR PROTECTIVE SYSTEMS WITH A LARGE NUMBER OF BUMPERS, SINCE THE NUMBER OF DETERMINANTS AND THE ORDER OF THE HIGHEST ORDERED DETERMINANT IS PRECISELY EQUAL TO THE NUMBER OF BUMPERS.



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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

**TRADITIONAL APPROACH**

- **THE EXTREMA THEOREM (ET) METHOD**
  - APPLIES TO FUNCTIONAL PREDICTORS ONLY
  - PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA
  - NUMBER OF DETERMINANTS TO BE COMPUTED IS EQUAL TO THE NUMBER OF BUMPERS
  - ORDER OF HIGHEST ORDERED DETERMINANT IS EQUAL TO THE NUMBER OF BUMPERS
  - REQUIRES EVALUATION OF PARTIAL DERIVATIVES
  - HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS

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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES (CONTINUED)

CONTRARY TO THE TRADITIONAL EXTREMA THEOREM APPROACH, THE GEOMETRIC PROGRAMMING TECHNIQUE PROVIDES THE GLOBAL OPTIMIZATION OF THE PROBLEM, PROVIDED IT IS FORMULATED IN POSYNOMIAL FORM. A POSYNOMIAL IS A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND POSITIVE VALUES OF THE INDEPENDENT VARIABLES. A QUICK REVIEW OF THE VARIABLES SHOWN UNDER THE IDEALIZED SPACECRAFT IMPACT SCENARIO SHOWS THAT THE VARIABLES ASSOCIATED WITH THIS PROBLEM ARE INHERENTLY POSITIVE-VALUED. THUS, THE ONLY REQUIREMENT FOR GLOBAL OPTIMIZATION OF THESE TYPES OF PROBLEMS IS THAT THE IMPACT PREDICTOR BE A POLYNOMIAL WITH POSITIVE COEFFICIENTS. ANOTHER ADVANTAGE TO GEOMETRIC PROGRAMMING IS THE METHOD'S ABILITY TO ACCOMMODATE MANY TYPES OF INEQUALITY CONSTRAINTS.



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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES (Continued)

## ALTERNATIVE APPROACH

- **THE GEOMETRIC PROGRAMMING (GP) METHOD**
  - EMPLOYS THE ARITHMETIC-GEOMETRIC INEQUALITY
  - APPLIES TO POSYNOMIALS (POSITIVE-VALUED POLYNOMIALS) ONLY
  - RESULTS IN GLOBAL OPTIMIZATION OF THE POSYNOMIAL
  - ACCOMMODATES MOST INEQUALITY CONSTRAINTS

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# APPLICATIONS OF OPTIMIZATION METHODOLOGY

THE NYSMITH EQUATION WITH VARIABLE DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER, WALL, OR PROJECTILE DENSITIES. THUS, WE SAY THAT THE NYSMITH PREDICTOR FORMS AN INCOMPLETE SET OF PARAMETERS. THE NYSMITH PREDICTOR IS ANALYZED BY BOTH OPTIMIZATION TECHNIQUES FOR THE ZERO DEGREE-OF-DIFFICULTY CASE WITH CONSISTENT RESULTS. IT IS ANALYZED USING GEOMETRIC PROGRAMMING ONLY FOR THE TWO DEGREE-OF-DIFFICULTY CASE, SINCE THE EXTREMA THEOREM METHOD DOES NOT HANDLE INEQUALITY CONSTRAINTS.

# APPLICATIONS OF OPTIMIZATION METHODOLOGY

- THE NYSMITH EQUATION

$$\frac{t_2}{d} = \frac{5.08\, V^{.278}}{\left(\frac{t_1}{d}\right)^{.528} \left(\frac{h}{d}\right)^{1.39}} , \quad \text{valid for}$$

$$\frac{t_1}{d} \leqslant 0.5 \quad \text{and} \quad \frac{t_2}{d} \leqslant 1.0 ,$$

where

$V$ = projectile velocity,
$d$ = projectile diameter,
$t_1$ = bumper thickness,
$t_2$ = wall thickness,
$h$ = bumper wall separation

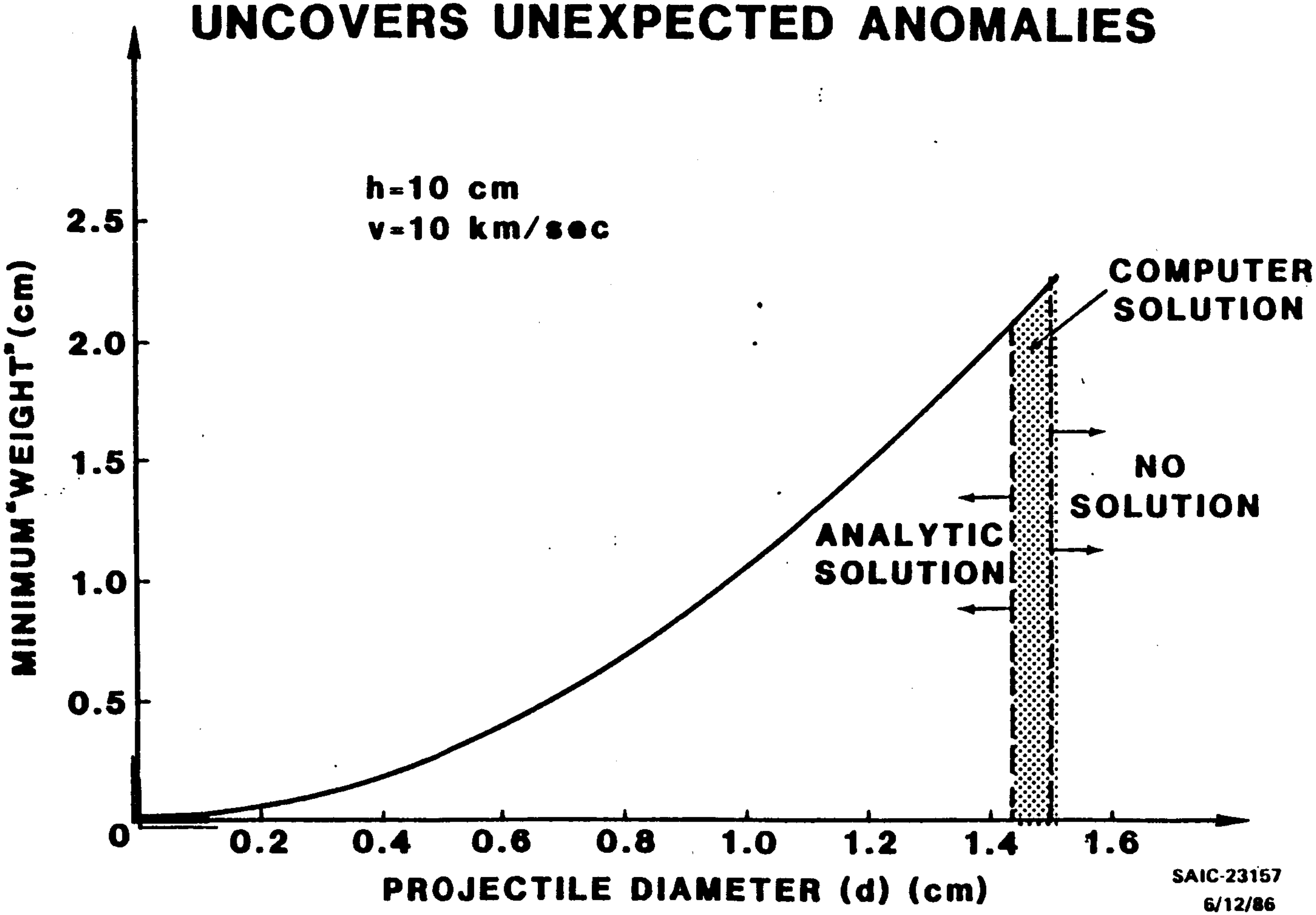
— INCOMPLETE SET OF PARAMETERS

— ANALYZED BY BOTH METHODS FOR ZERO DEGREE OF DIFFICULTY CASE (METHODOLOGY CONSISTENT) AND BY GP METHOD FOR 2 DEGREE OF DIFFICULTY CASE.

# GP METHOD SEPARATES SOLUTION REGIONS AND UNCOVERS UNEXPECTED ANOMALIES

THE DEPENDENCE OF OPTIMAL DESIGN ON PROJECTILE DIAMETER IS SHOWN FOR A HYPOTHETICAL SCENARIO. IT TURNS OUT THAT THERE ARE THREE SOLUTION REGIONS ASSOCIATED WITH THE NYSMITH PREDICTOR. IN THE ANALYTIC SOLUTION REGION, IT IS DISCOVERED THAT THE MINIMUM "WEIGHT" MAY BE WRITTEN ANALYTICALLY IN TERMS OF THE SOLUTION PARAMETERS. IN THE COMPUTER SOLUTION REGION, THE GEOMETRIC PROGRAMMING DUAL VARIABLES MUST BE ITERATED TO OBTAIN THE OPTIMAL SOLUTION. FINALLY, IT IS FOUND THAT THERE EXISTS A REGION OF NO SOLUTION WHICH CORRESPONDS WITH A THIRD, PREVIOUSLY UNDISCOVERED, INEQUALITY CONSTRAINT TO THE NYSMITH PREDICTOR. THIS INEQUALITY CONSTRAINT IS INDEPENDENT OF THE ORIGINAL TWO CONSTRAINTS AND RESTRICTS THE APPLICABILITY OF THE NYSMITH PREDICTOR.

# GP METHOD SEPARATES SOLUTION REGIONS AND UNCOVERS UNEXPECTED ANOMALIES

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# AVERAGE CUMULATIVE TOTAL METEOROID FLUX-MASS MODEL FOR 1 A.U.

THE RELATIONSHIP BETWEEN METEOROID FLUX AND MASS WAS EXTRACTED FROM NASA TM-86466, "A REVIEW OF MICROMETEOROID FLUX MEASUREMENTS AND MODELS FOR LOW ORBITAL ALTITUDES OF THE SPACE STATION", BY MICHAEL SUSKO, SEPTEMBER, 1984.

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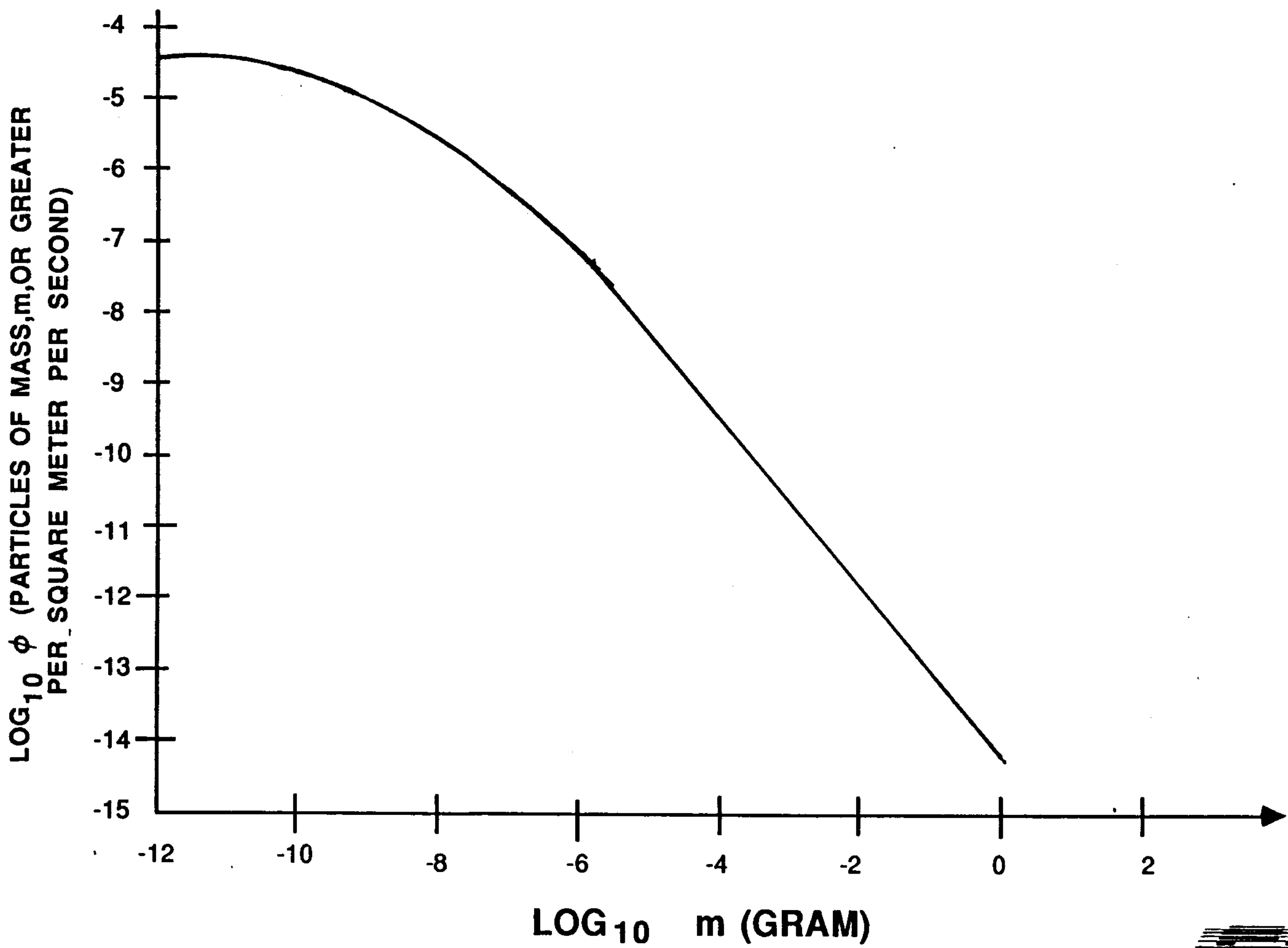
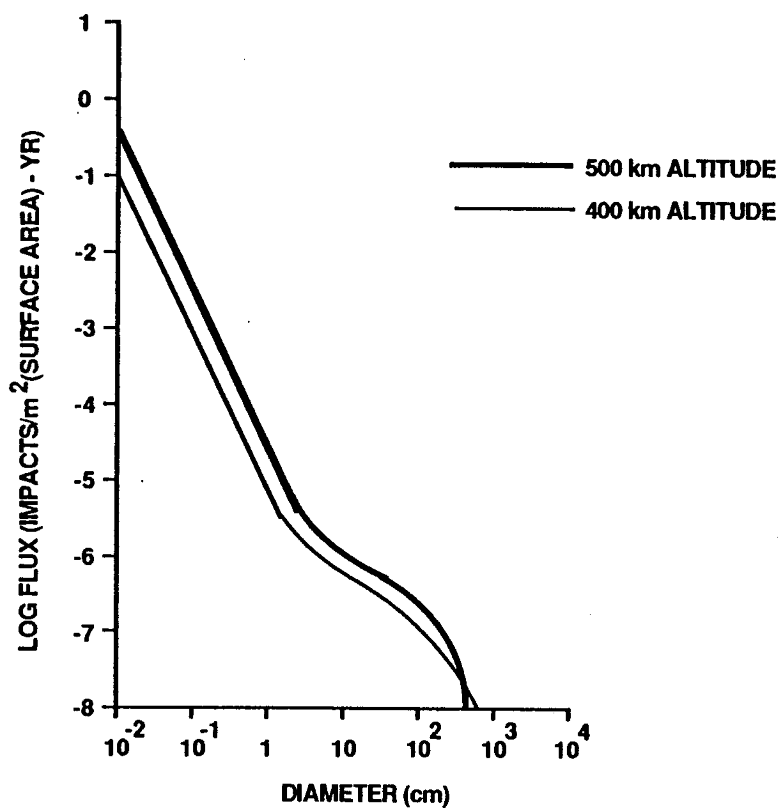
## AVERAGE CUMULATIVE TOTAL METEOROID FLUX-MASS MODEL FOR 1 A.U.



# 1990's AVERAGE ENVIRONMENT

THE AVERAGE ORBITAL DEBRIS ENVIRONMENT FOR THE 1990's IS SHOWN FOR 400 AND 500 Km ALTITUDES. THIS DATA WAS EXTRACTED FROM JSC-20001, "ORBITAL DEBRIS ENVIRONMENT FOR SPACE STATION", DONALD J. KESSLER. NOTE THE SHARP INFLECTION POINTS OCCURRING AT A DIAMETER OF 1 CM.

# 1990's AVERAGE ENVIRONMENT

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# SECTION II

## NYSMITH PREDICTOR APPLIED TO IDEALIZED SCENARIO

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# WHAT YOU WILL SEE IN SECTION II

- A COMPARISON OF METEOROID AND DEBRIS ENVIRONS FOR THE NYSMITH PREDICTOR-IDEALIZED SCENARIO

- OPTIMAL THICKNESS DISTRIBUTIONS FOR THE NYSMITH PREDICTOR

- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - PROJECTILE VELOCITY
  - MISSION RISK
  - MISSION DURATION

## BASELINE DESIGN PARAMETERS

THE MARCH 1987 BASELINE DESIGN PARAMETERS USED FOR ANALYSIS OF THE NYSMITH PREDICTOR ARE SHOWN. THESE PARAMETERS IMPLY A BASELINE OPTIMAL (NYSMITH) DESIGN THAT IS ROUGHLY 1.5 TIMES THE CURRENT DESIGN.

# BASELINE DESIGN PARAMETERS

**DESIGN ASSUMPTIONS**

| | | | |
|---|---|---|---|
| $P_o$ | = | 0.97 | (PROBABILITY OF NO PENETRATION) |
| T | = | 10 YRS | (MISSION DURATION) |
| $A_d$ | = | 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = | 403 $m^2$ | (METEOROID AREA) |
| Alt | = | 500 km | (AVERAGE ALTITUDE) |
| $V_m$ | = | 20 km/sec | (AVERAGE METEOROID VELOCITY) |
| $V_D$ | = | 10 km/sec | (AVERAGE DEBRIS VELOCITY) |
| $\rho_m$ | = | 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = | 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| h | = | 10 cm | (BUMPER/WALL. SEPARATION) |

NYSMITH EQUATION
IDEALIZED SCENARIO

**OPTIMAL DESIGN (BALLISTIC LIMIT)**

**BUMPER**

$t_{10}$ = 0.26 cm (0.10 IN)

**WALL**

$t_{20}$ = 0.48 cm (0.19 IN)

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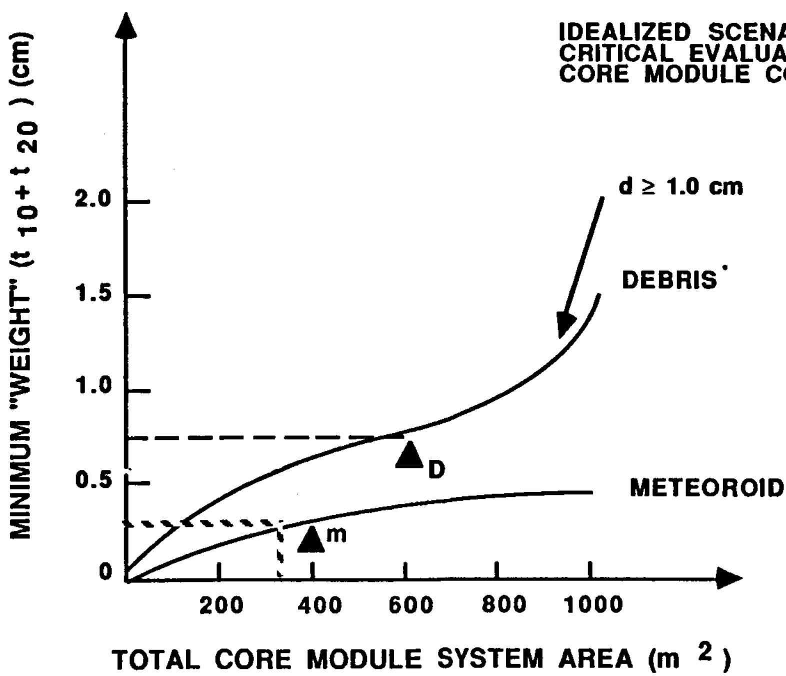
## DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

SHOWN IS THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS. THE DEBRIS ENVIRONMENT DRIVES DESIGN FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM. THE EQUIVALENT DEBRIS AREA FOR THE CURRENT DESIGN ("WEIGHT" ~ 0.48 CM) IS ONLY 330 SQUARE METERS.

# DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS




**EQUIVALENT DEBRIS AREA FOR CURRENT DESIGN ≈330M²**

- $P_o = 0.97$
- $T = 10$ yrs
- Alt = 500 km
- $V_m = 20$ km/sec
- $V_D = 10$ km/sec
- $\rho_m = 0.5$ gm/cm³
- $\rho_D = 2.81$ gm/cm³
- $h = 10$ cm

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## DEBRIS ENVIRONMENT DRIVES DESPITE $P_O$ REDUCTION

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A $P_0$ OF 0.95 IS ILLUSTRATED. ALTHOUGH THIS REDUCTION IN Po REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

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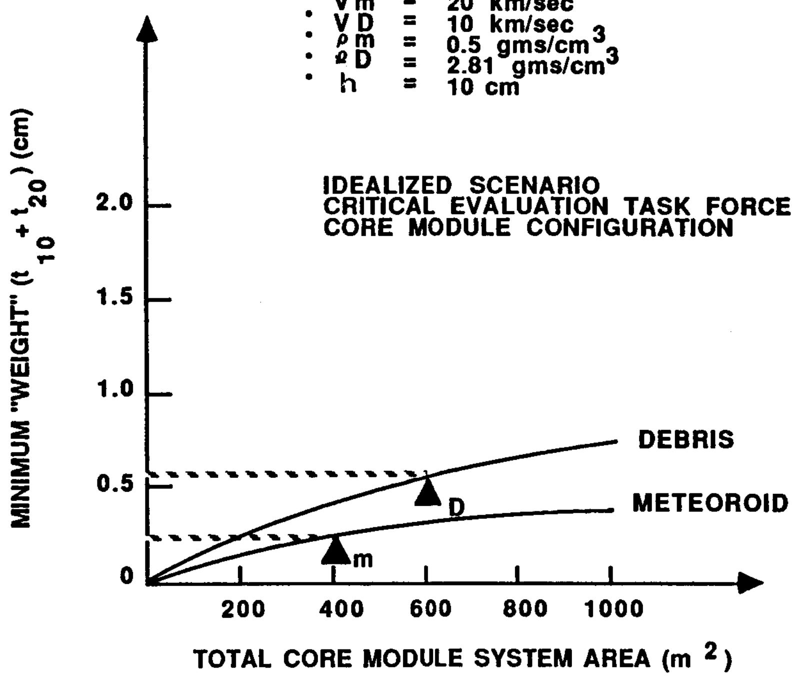
# DEBRIS ENVIRONMENT DRIVES DESPITE Po REDUCTION

- Po = 0.95
- T = 10 YRS
- Alt = 500 km
- Vm = 20 km/sec
- VD = 10 km/sec
- $\rho_m$ = 0.5 gms/cm$^3$
- $\rho_D$ = 2.81 gms/cm$^3$
- h = 10 cm

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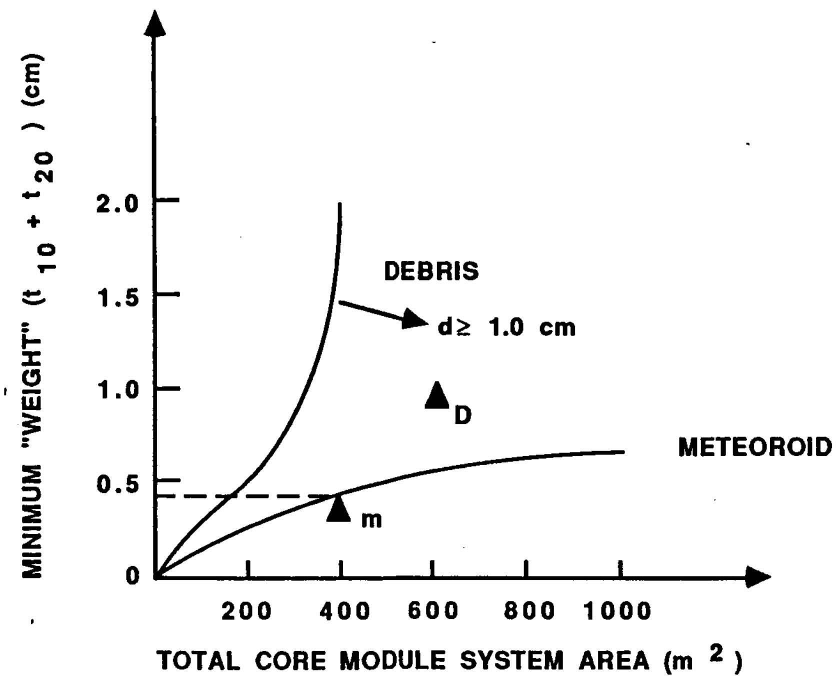
# INCREASE IN $P_0$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED

SHOWN IS THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A $P_0$ OF 0.99. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PARTICLE INDUCED BY SO LARGE A $P_0$ EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

# INCREASE IN $P_O$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED

- $P_o$ = 0.99
- T = 10 YRS
- Alt = 500 km
- $V_m$ = 20 km/sec
- $V_D$ = 10 km/sec
- $\rho_m$ = 0.5 gms/cm$^3$
- $\rho_D$ = 2.81 gms/cm$^3$
- h = 10 cm
- IDEALIZED SCENARIO
- CRITICAL EVALUATION TASK FORCE CORE MODULE CONFIGURATION

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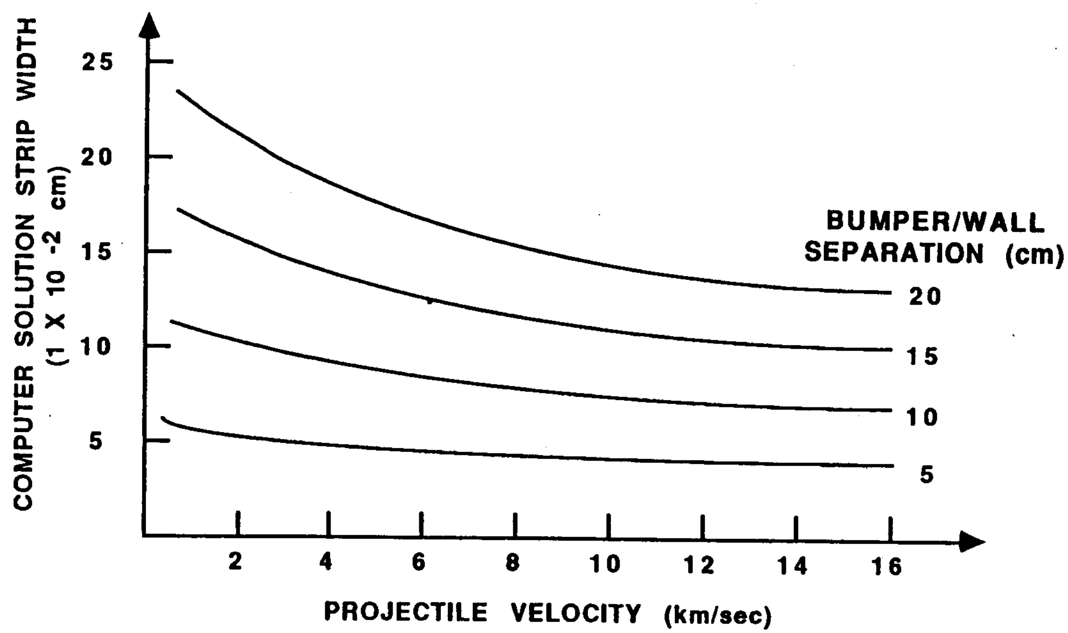
# COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

SHOWN IS THE WIDTH OF THE COMPUTER SOLUTION REGION FOR THE NYSMITH EQUATION AS A FUNCTION OF PROJECTILE VELOCITY, FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS WIDTH REPRESENTS THE DIFFERENCE IN THE PROJECTILE DIAMETER AT THE BEGINNING OF THE NO SOLUTION REGION AND THE END OF THE ANALYTICAL SOLUTION REGION. CLEARLY, FOR PARAMETERS IN THE NEIGHBORHOOD OF THE BASELINE PARAMETERS, THIS REGION IS VERY NARROW. IN FACT, THE REGION IS NARROW ENOUGH TO BE APPROXIMATED BY THE ANALYTICAL (UNCONSTRAINED) SOLUTION TO THE NYSMITH EQUATION, THUS REDUCING COMPUTER USAGE.

# COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

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MC 9 OT 5/87 RWL

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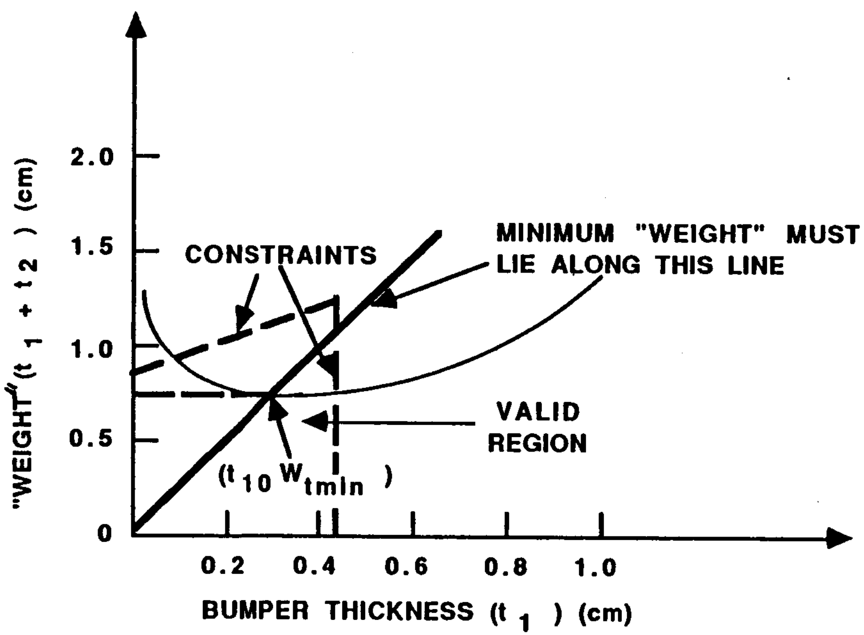
# GP METHOD CONFIRMS THE MINIMUM WEIGHT

THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP) IS SHOWN. THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY. NOTE THAT THE MINIMUM "WEIGHT" LINE DOES NOT INTERSECT THE INTERSECTION OF THE INEQUALITY CONSTRAINTS. THIS OFFSET ESTABLISHES THE COMPUTER SOLUTION REGION AS DISCUSSED EARLIER.

# GP METHOD CONFIRMS THE MINIMUM WEIGHT




- $d = 0.84$ cm
- $V = 10$ km/sec
- $h = 10$ cm
- NYSMITH EQUATION
- IDEALIZED SCENARIO

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MC10 OT 5/87 RWL

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# OPTIMAL THICKNESSES VARY LINEARLY WITH "MINIMUM WEIGHT"

SHOWN ARE THE LINEAR RELATIONSHIPS BETWEEN THE OPTIMAL THICKNESSES OF THE BUMPER AND WALL AND THE MINIMUM "WEIGHT" AS REPRESENTED BY THE SUM OF BUMPER AND WALL THICKNESSES. THE LINES, EMANATING FROM THE ORIGIN, HAVE SLOPES OF 0.35 AND 0.65 FOR THE BUMPER AND WALL, RESPECTIVELY.



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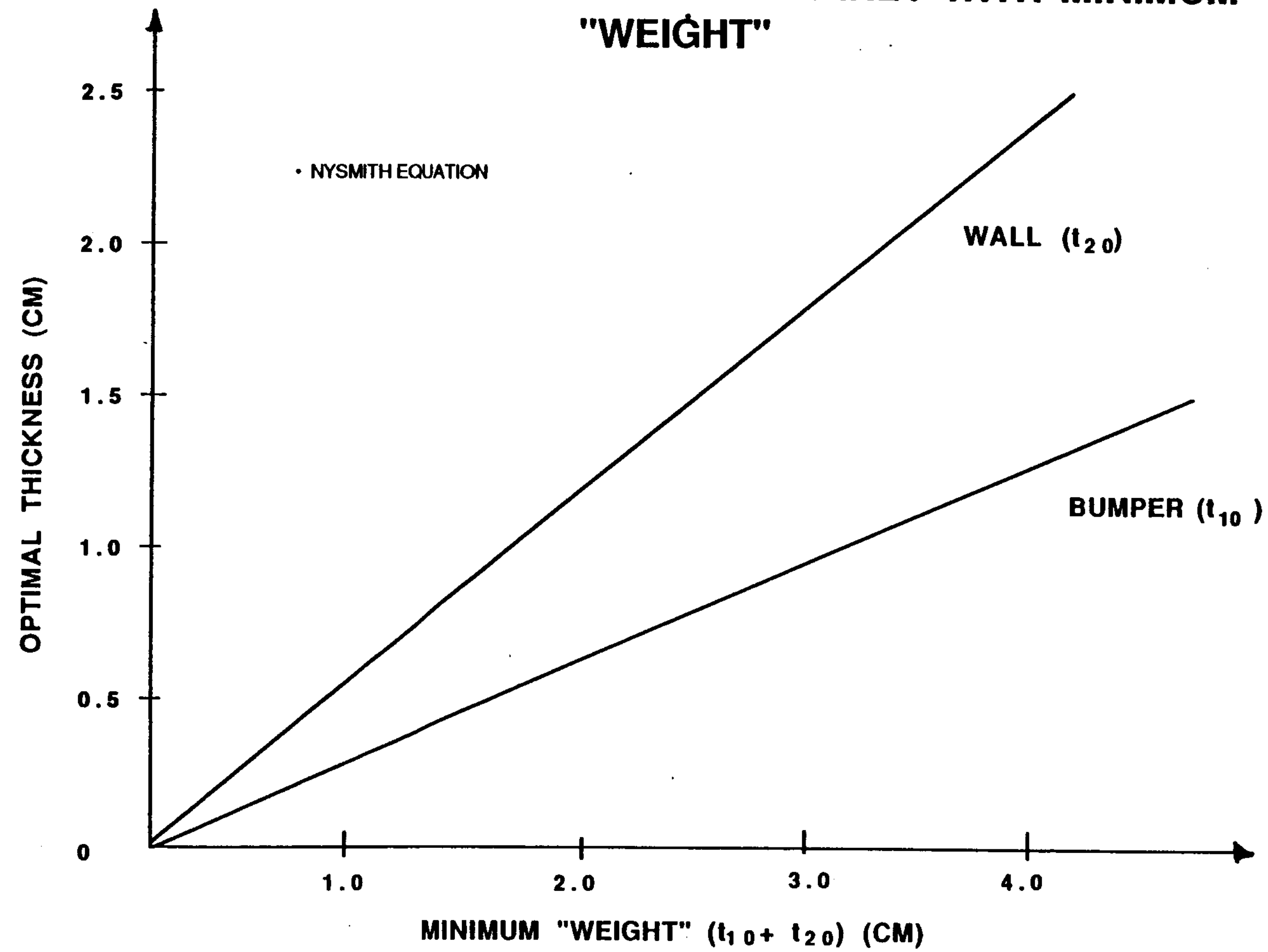
# OPTIMAL THICKNESSES VARY LINEARLY WITH MINIMUM "WEIGHT"




2 OT RLK

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# OPTIMAL WALL THICKNESS VARIES LINEARLY WITH OPTIMAL BUMPER THICKNESS

SHOWN IS THE LINEAR RELATIONSHIP BETWEEN THE OPTIMAL WALL THICKNESS AND THE OPTIMAL BUMPER THICKNESS FOR THE NYSMITH PREDICTOR. THE LINE EMANATES FROM THE ORIGIN AND HAS A SLOPE OF APPROXIMATELY 1.92.



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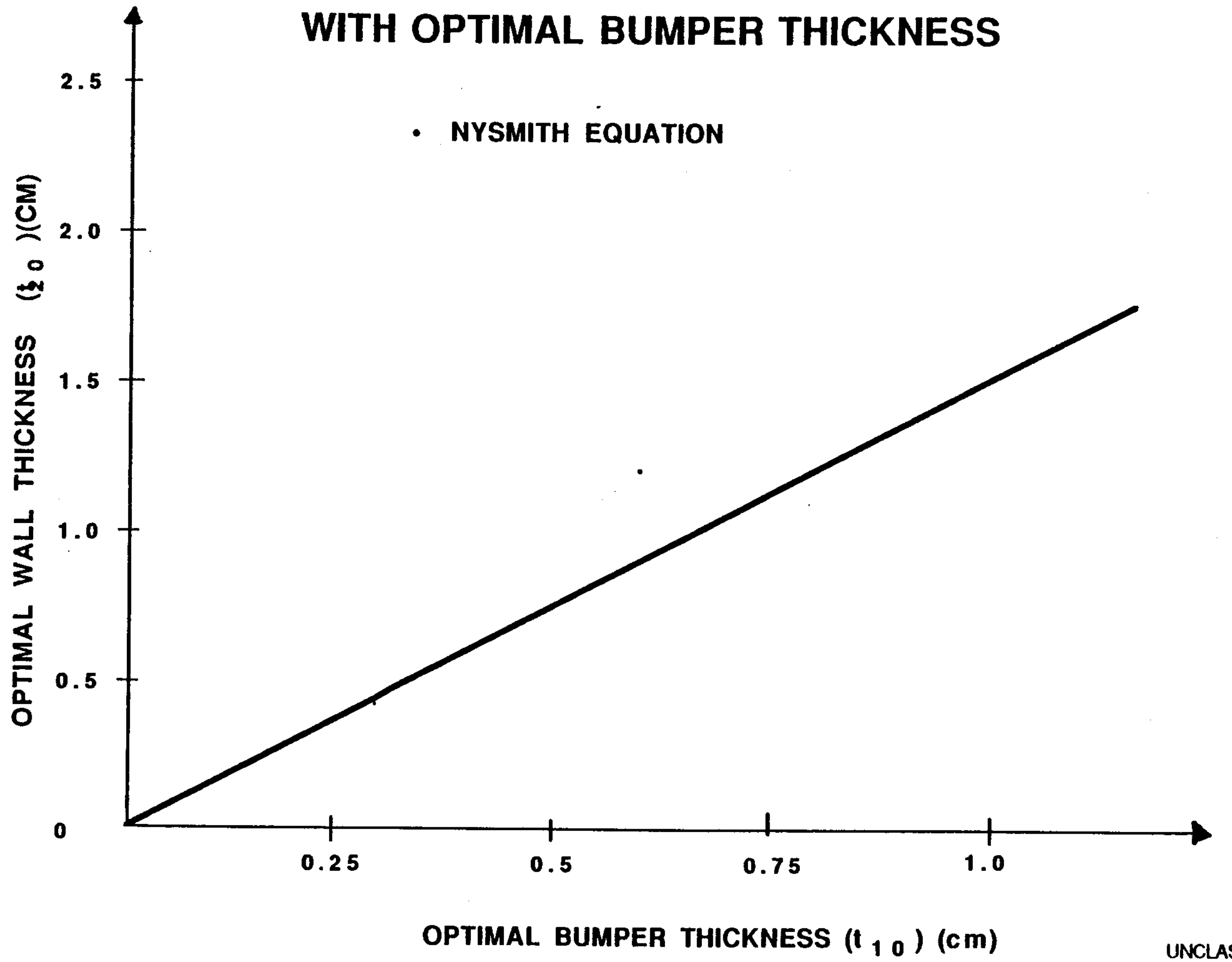
# OPTIMAL WALL THICKNESS VARIES LINEARLY WITH OPTIMAL BUMPER THICKNESS

- NYSMITH EQUATION

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MC11 OT RWL

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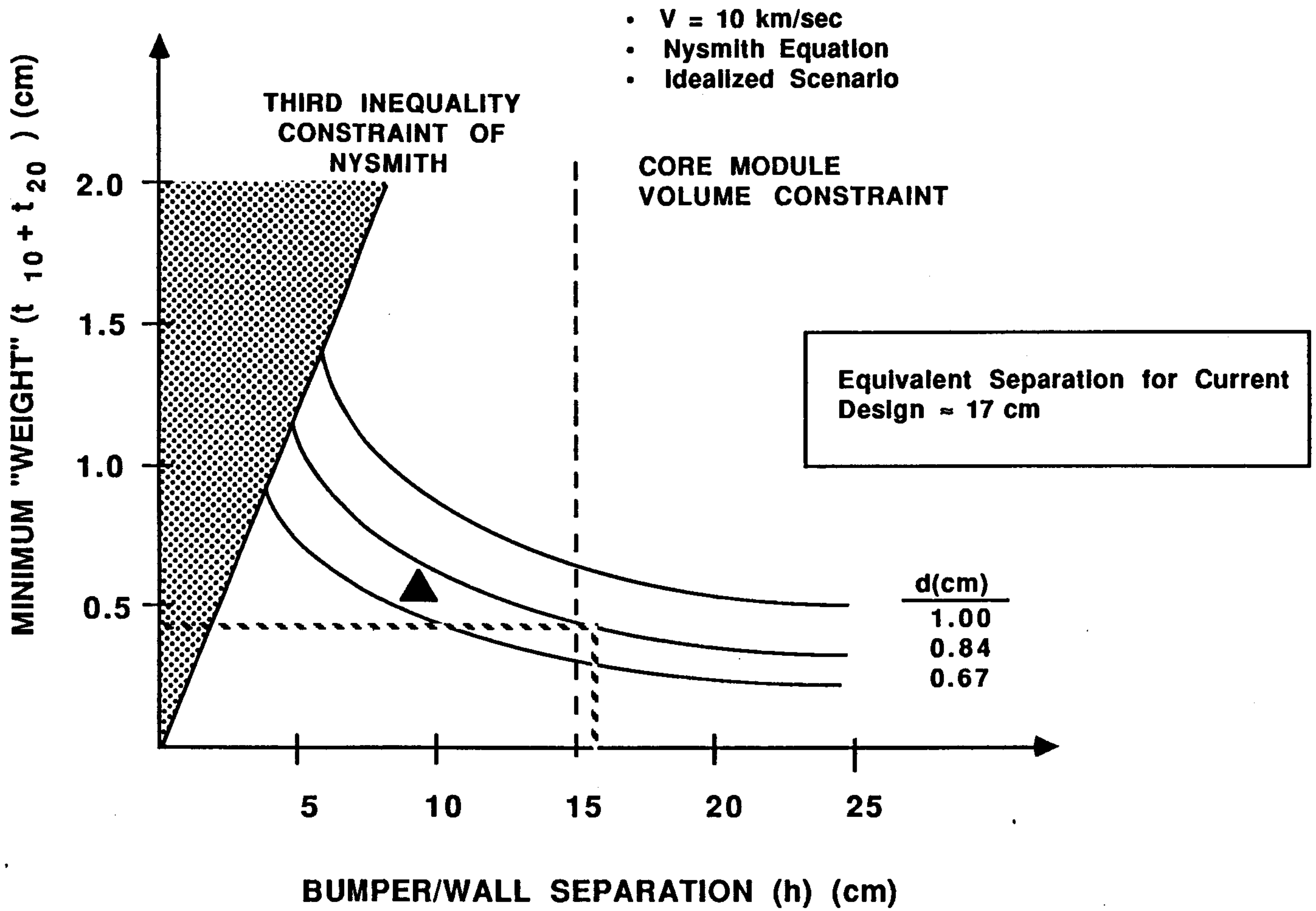
## OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAY-OFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15 CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARD THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN, AND THE REGION TO THE LEFT OF THIS LINE IS INFEASIBLE.

# OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

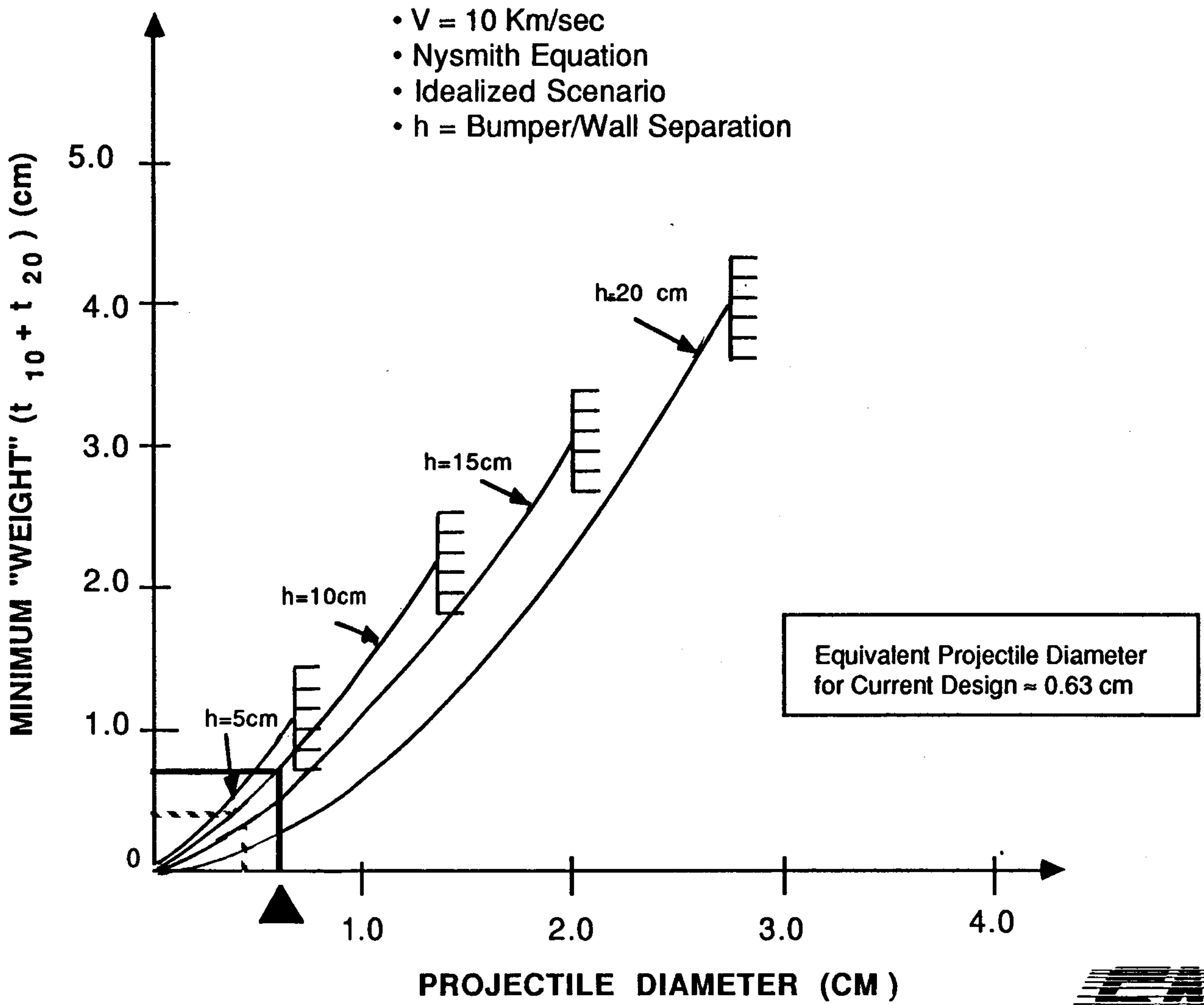


# GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

ONE IMPORTANT SENSITIVITY ANALYSIS IS THE EFFECT OF THREAT, IN TERMS OF SPACE DEBRIS PROJECTILE DIAMETER, ON OPTIMAL DESIGN.

THE EFFECT OF PROJECTILE DIAMETER ON "WEIGHT" IS SHOWN FOR VARIOUS BUMPER/WALL SEPARATIONS. THE EQUIVALENT PROJECTILE DIAMETER INDUCED BY THE CURRENT DESIGN IS ROUGHLY 0.63 CM. THE LIMITS IMPOSED ON PROJECTILE DIAMETER BY THE THIRD INEQUALITY CONSTRAINT FOR EACH CURVE ARE SHOWN TO THE RIGHT. AGAIN, THESE CURVES LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

## GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN



# OPTIMAL DESIGN IS SENSITIVE TO THREAT

**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.**

BM20-9/1

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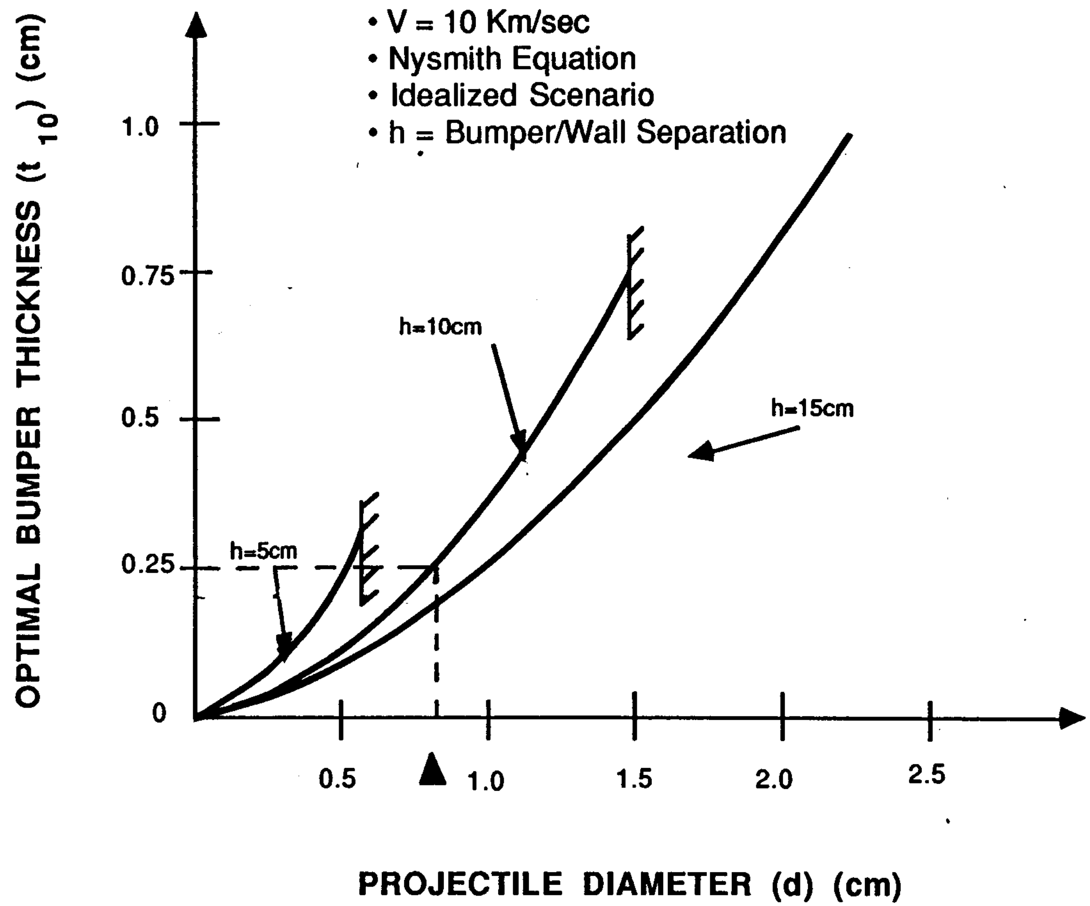
## OPTIMAL DESIGN IS SENSITIVE TO THREAT



# OPTIMAL DESIGN IS SENSITIVE TO THREAT

**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS FOR A PROJECTILE VELOCITY OF 5 KM/SEC IS SHOWN.**

BM21-9/1

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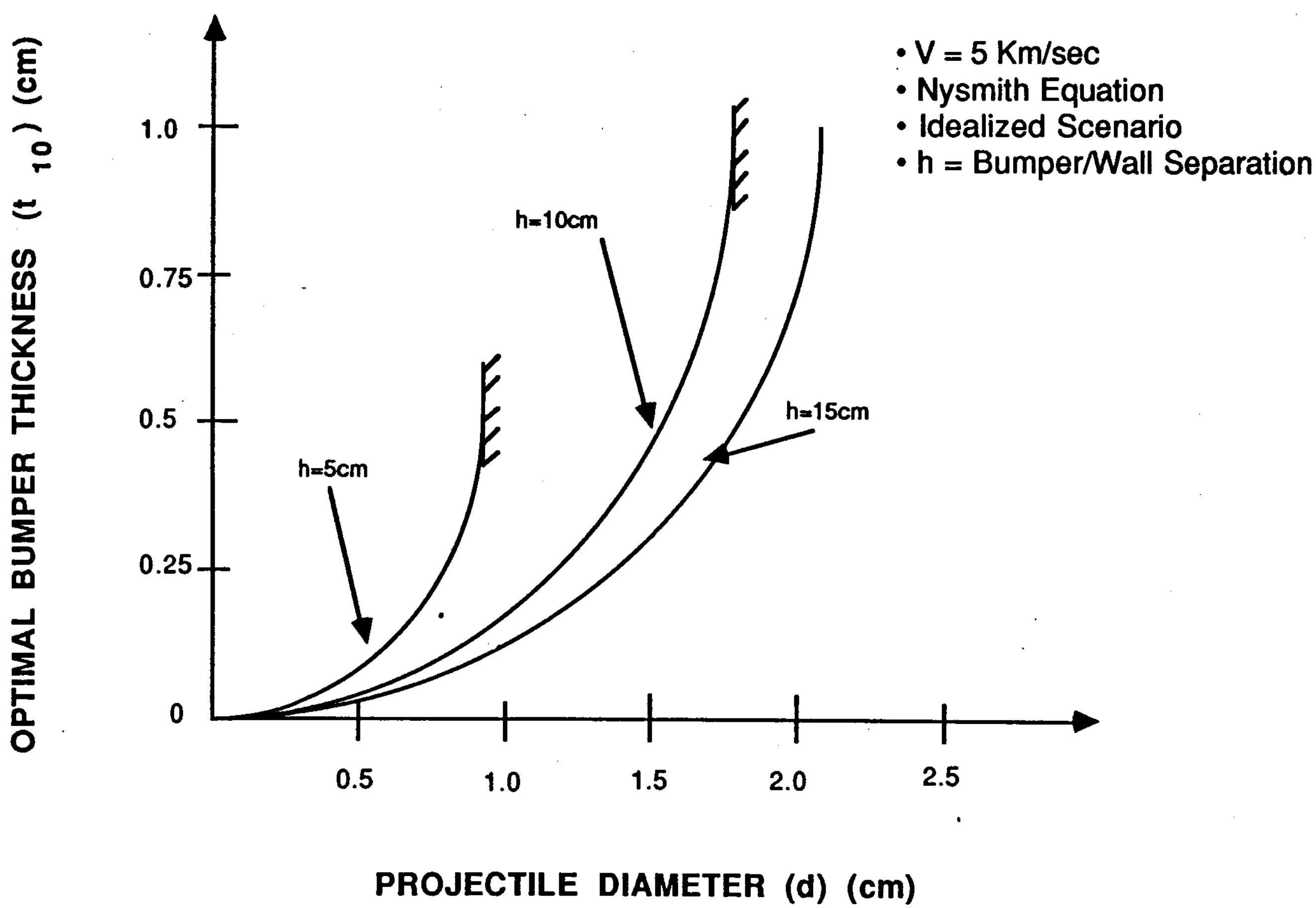
## OPTIMAL DESIGN IS SENSITIVE TO THREAT



# OPTIMAL DESIGN IS SENSITIVE TO THREAT

**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS FOR A PROJECTILE VELOCITY OF 16 KM/SEC IS SHOWN.**



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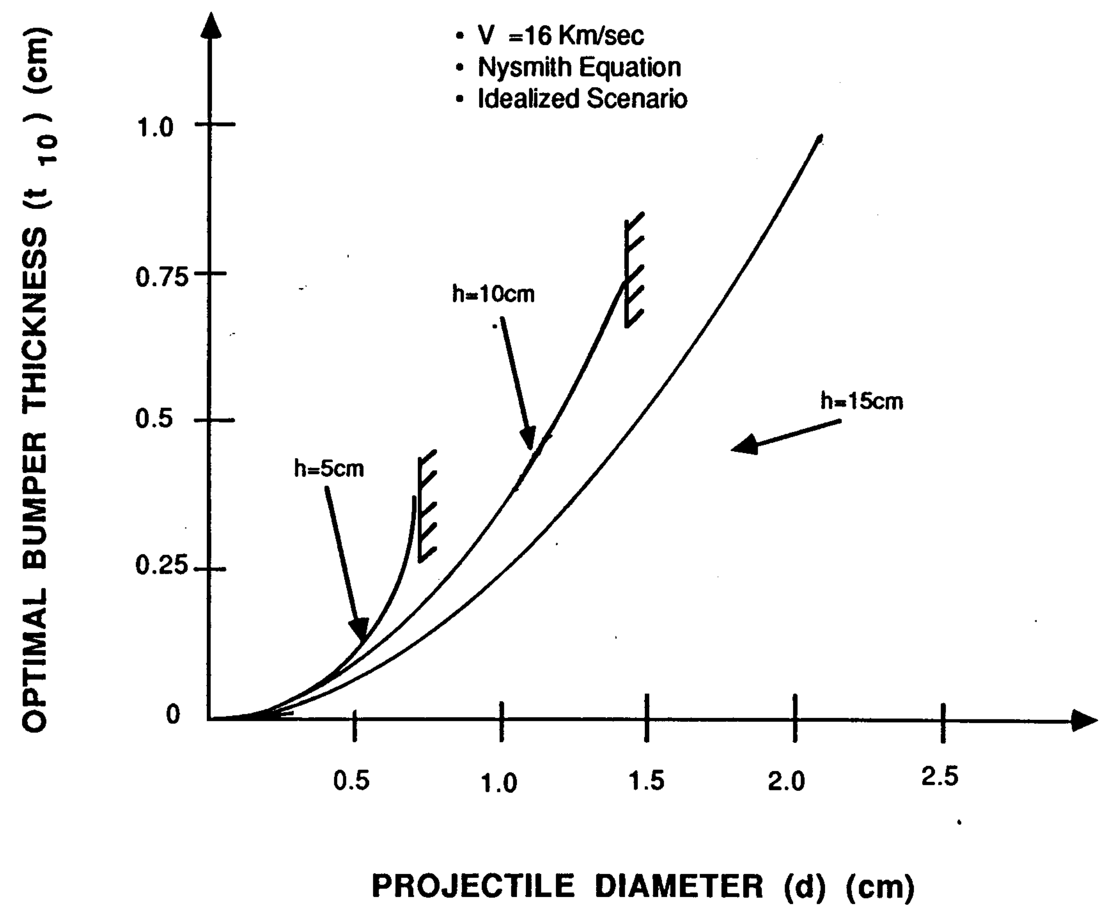
## OPTIMAL DESIGN IS SENSITIVE TO THREAT

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## GP METHOD PROVIDES THE MINIMUM BUMPER/WALL SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS

THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION IN TERMS OF THE MINIMUM BUMPER/WALL SEPARATION AS A FUNCTION OF PROJECTILE DIAMETER FOR VARIOUS PROJECTILE VELOCITIES IS SHOWN. THE BASELINE MINIMUM SEPARATION ALLOWED IS ROUGHLY 6 CM.



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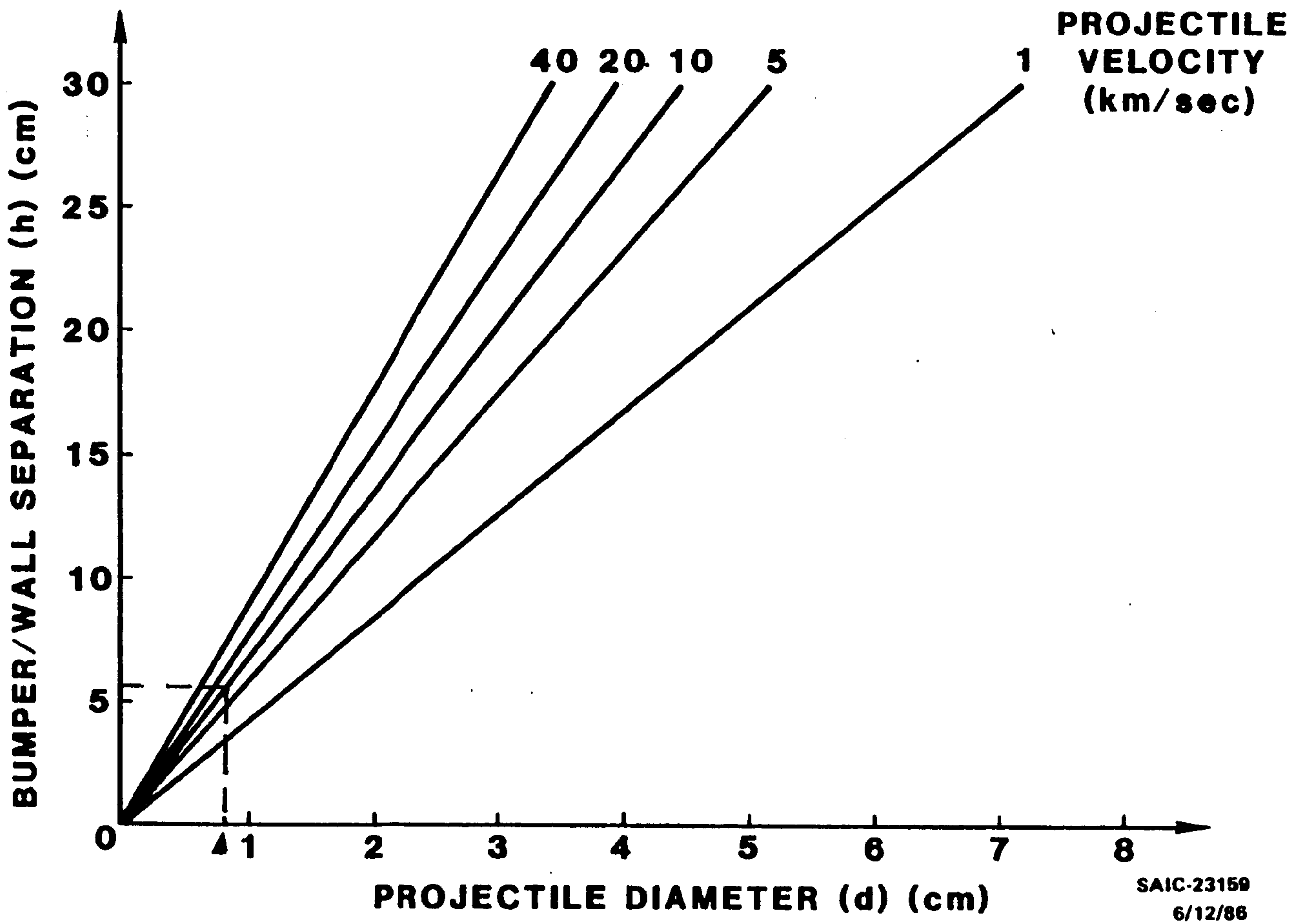
# GP METHOD PROVIDES THE MINIMUM BUMPER/WALL SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS

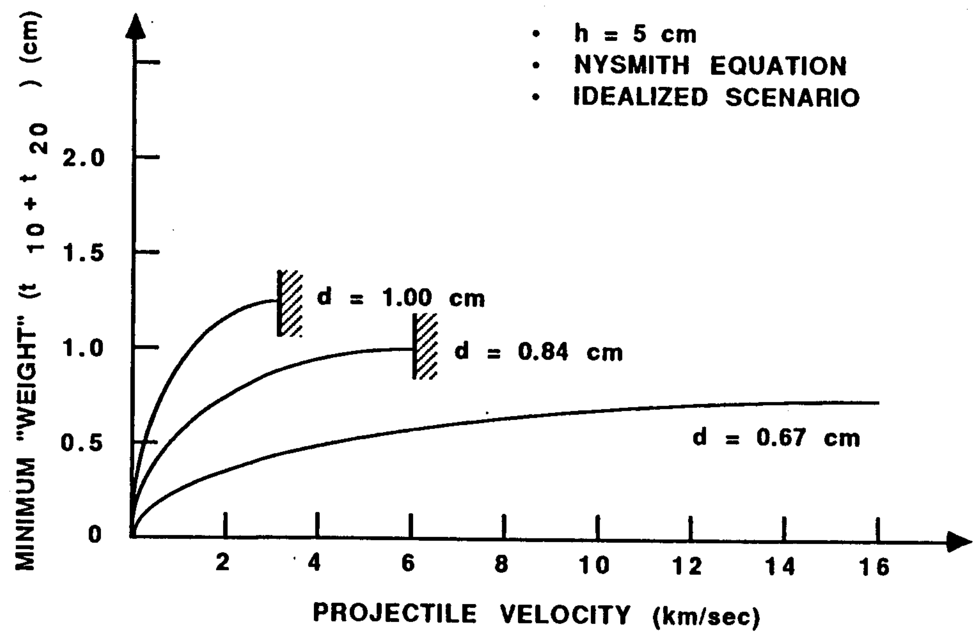



SAIC-23159
6/12/86

# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY. NOTE THAT THE EQUIVALENT PROJECTILE VELOCITY INDUCED BY THE CURRENT DESIGN IS 2.5 KM/SEC.

# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

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MC 12 OT 5/87 RWL

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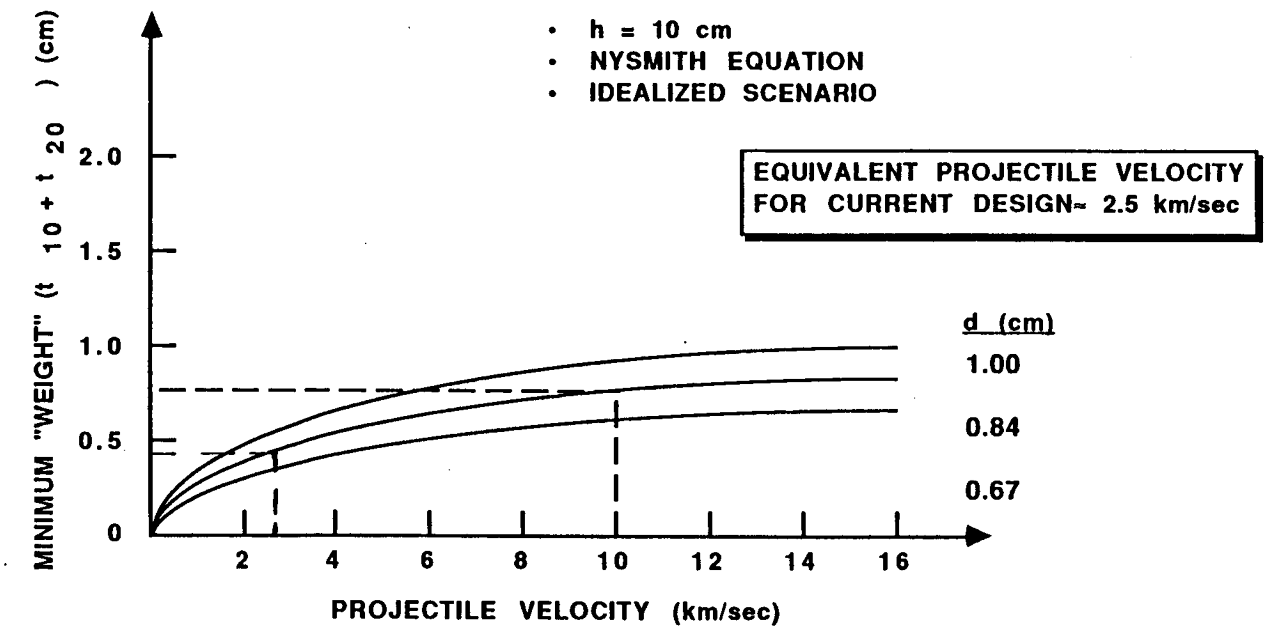
# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

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MC 13 OT 5/87 RWL

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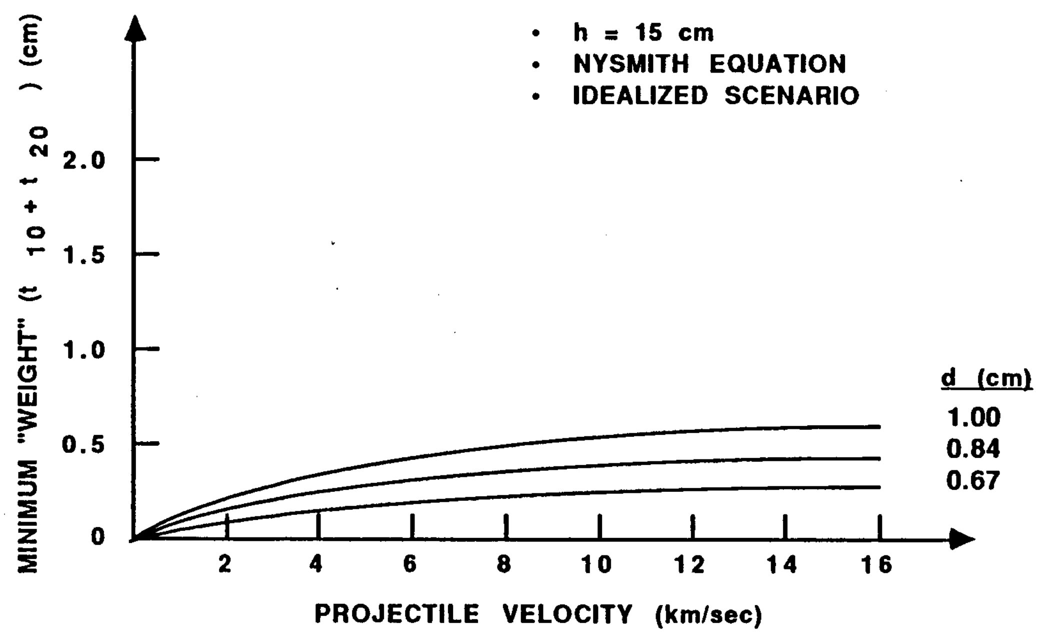
# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL SEPARATIONS IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK PLAYS A VERY SIGNIFICANT ROLE IN DETERMINING THE OPTIMAL DESIGN. NOTE THAT THE EQUIVALENT MISSION RISK INDUCED BY THE CURRENT DESIGN IS 5.8%, CORRESPONDING TO A $P_0$ OF 0.942.

BM25-9/1

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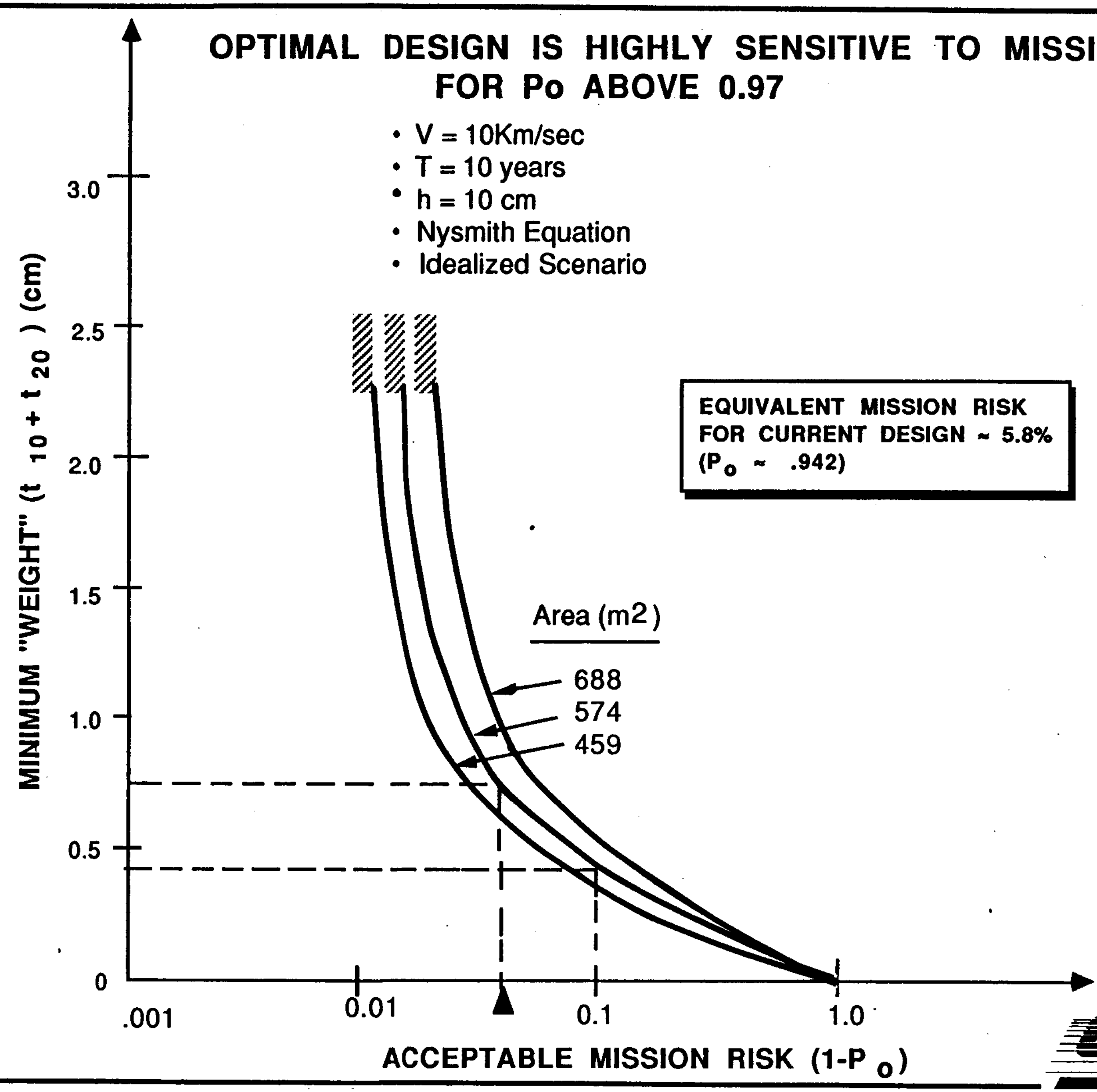
# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR Po ABOVE 0.97



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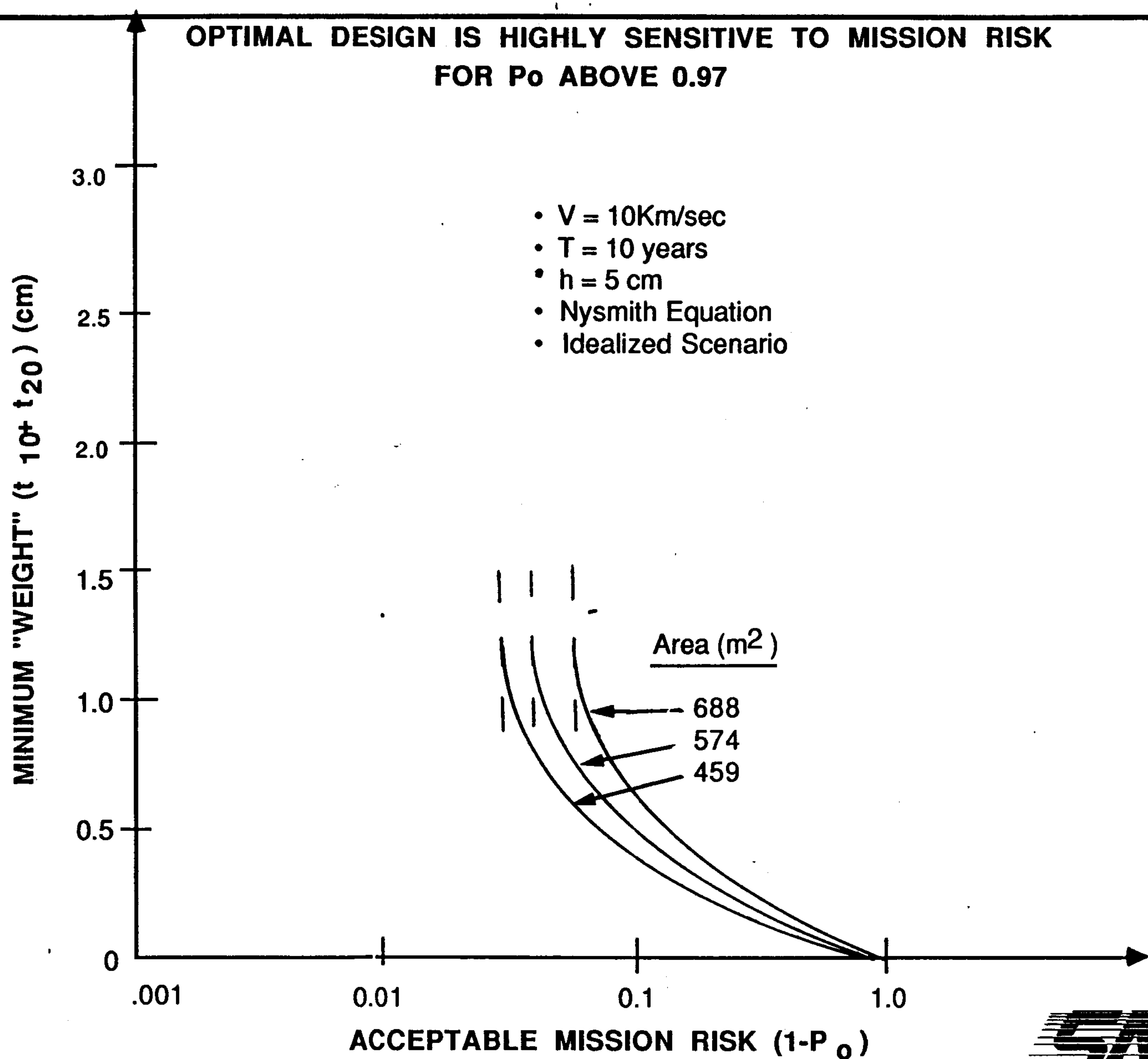
# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR Po ABOVE 0.97

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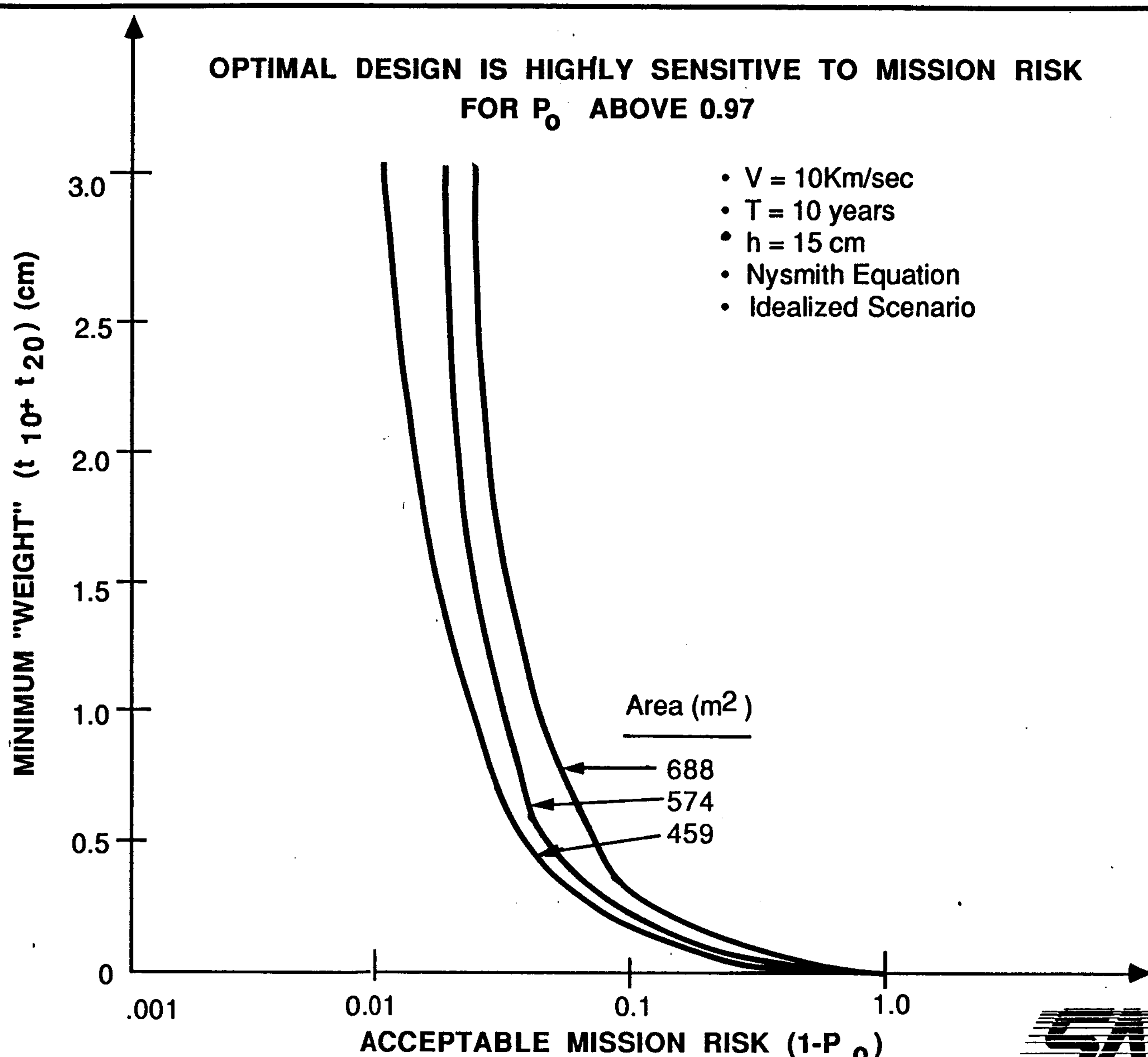
## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

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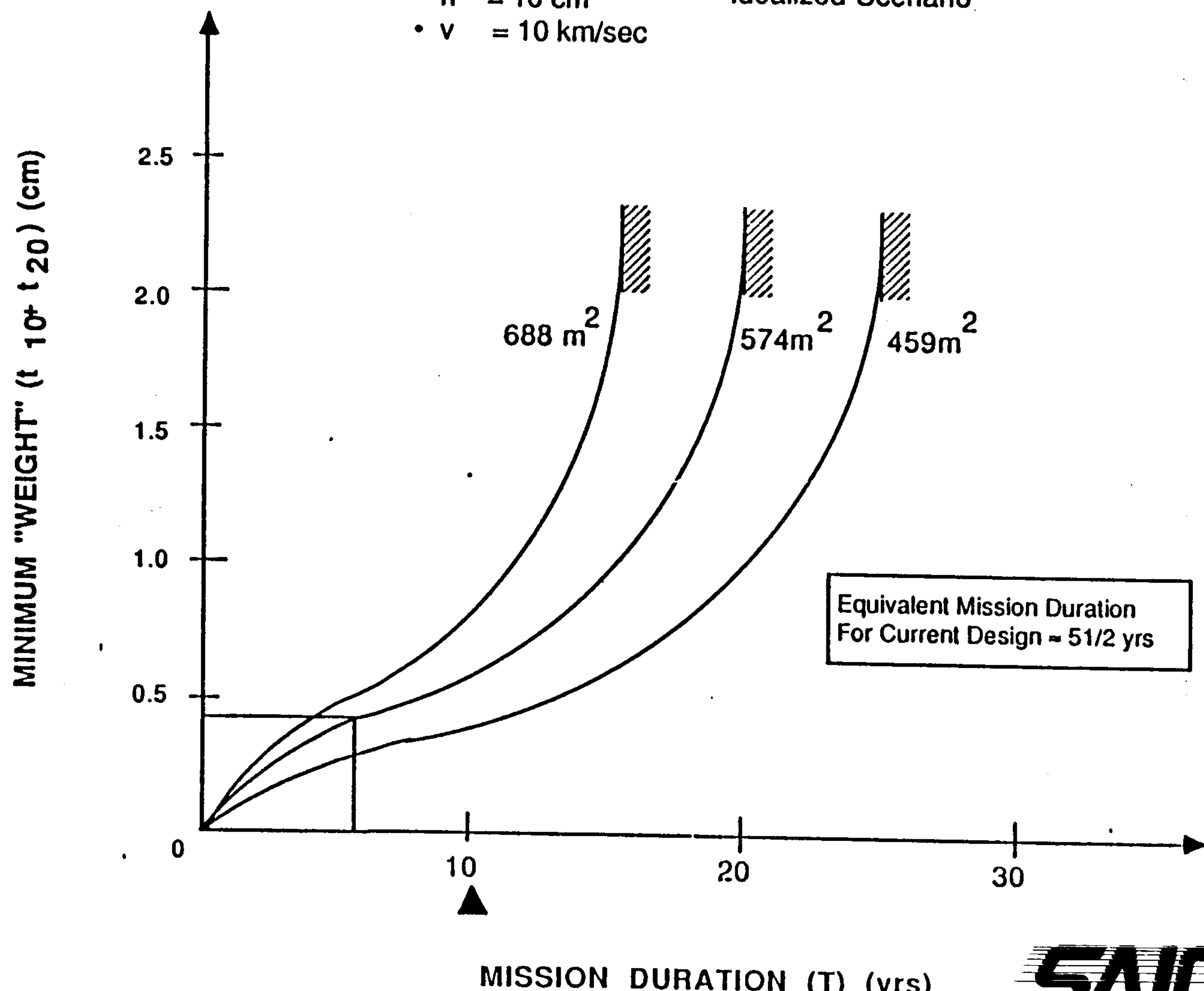
## OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT $P_0$s, THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE. THE INFLECTION IS DUE TO THE INFLECTION IN THE SPACE DEBRIS ENVIRONMENT CURVE AT 1 CM DIAMETER PARTICLES. THE EQUIVALENT MISSION DURATION FOR THE CURRENT DESIGN IS ROUGHLY 5.5 YEARS.

## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_o = 0.97$
- $h = 10$ cm
- $v = 10$ km/sec

- Nysmith Equation
- Idealized Scenario

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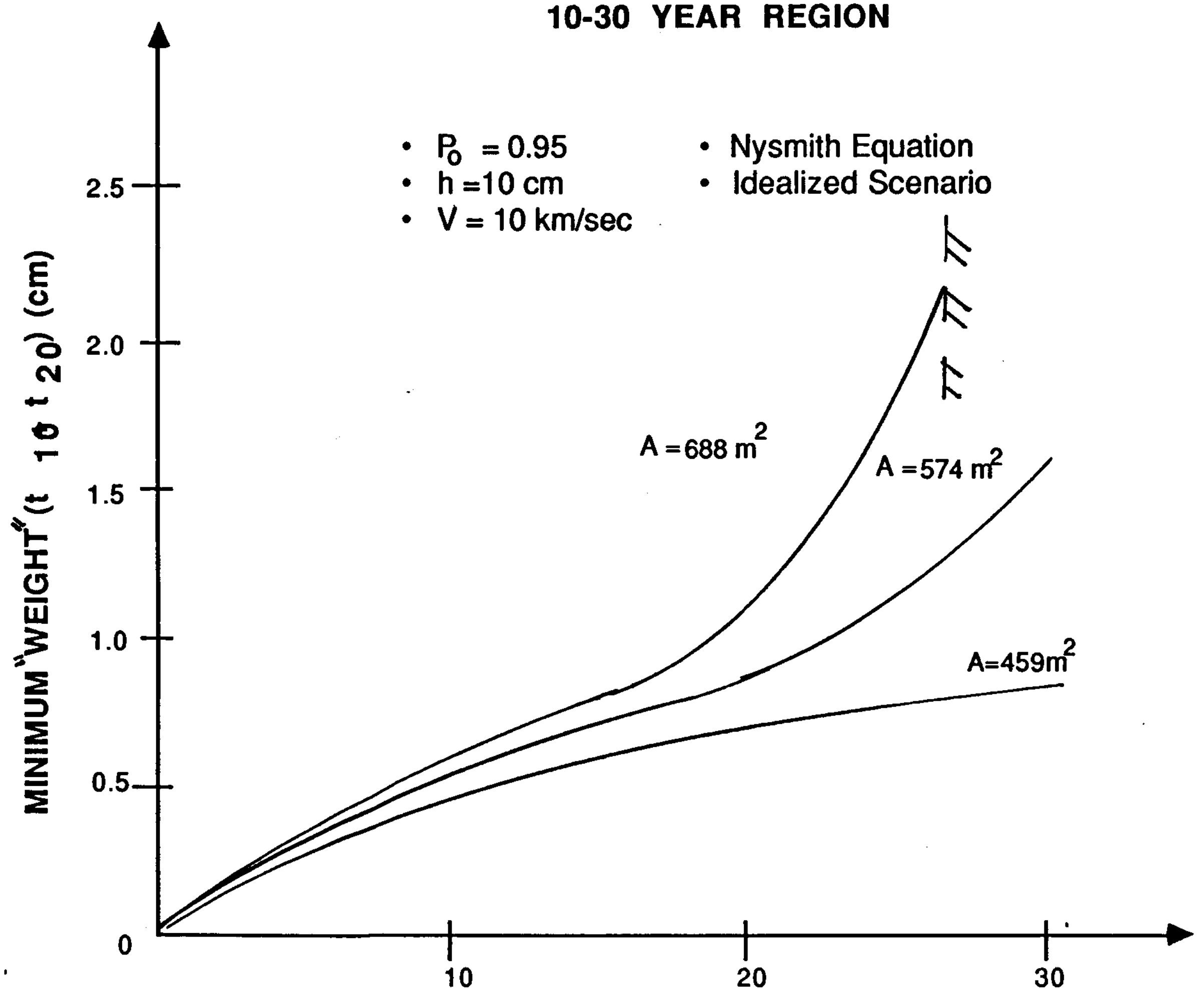
## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION



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# SECTION III

## NYSMITH PREDICTOR APPLIED TO CORE MODULE CONFIGURATION

BM40-9/1

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# WHAT YOU WILL SEE IN SECTION III

- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE NYSMITH PREDICTOR APPLIED TO THE CORE MODULE CONFIGURATION

- DESIGN TRADES, INCLUDING MINIMUM WEIGHT VERSUS:
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - PROJECTILE VELOCITY
  - MISSION RISK
  - MISSION DURATION

BM3 10/13

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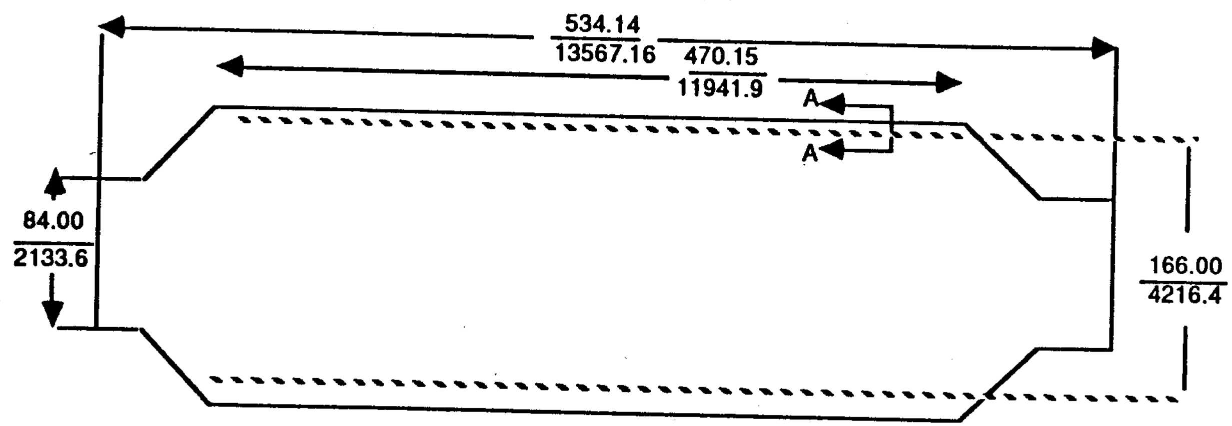
# BASELINE CORE MODULE CONFIGURATION

**SHOWN IS THE MARCH 1987 CORE MODULE CONFIGURATION. THIS IS USED TO OBTAIN THE OBJECTIVE FUNCTION WHICH ESTIMATES ITS WEIGHT.**

## BASELINE CORE MODULE CONFIGURATION




- TOP DIMENSIONS IN INCHES
- BOTTOM DIMENSIONS IN MILLIMETERS

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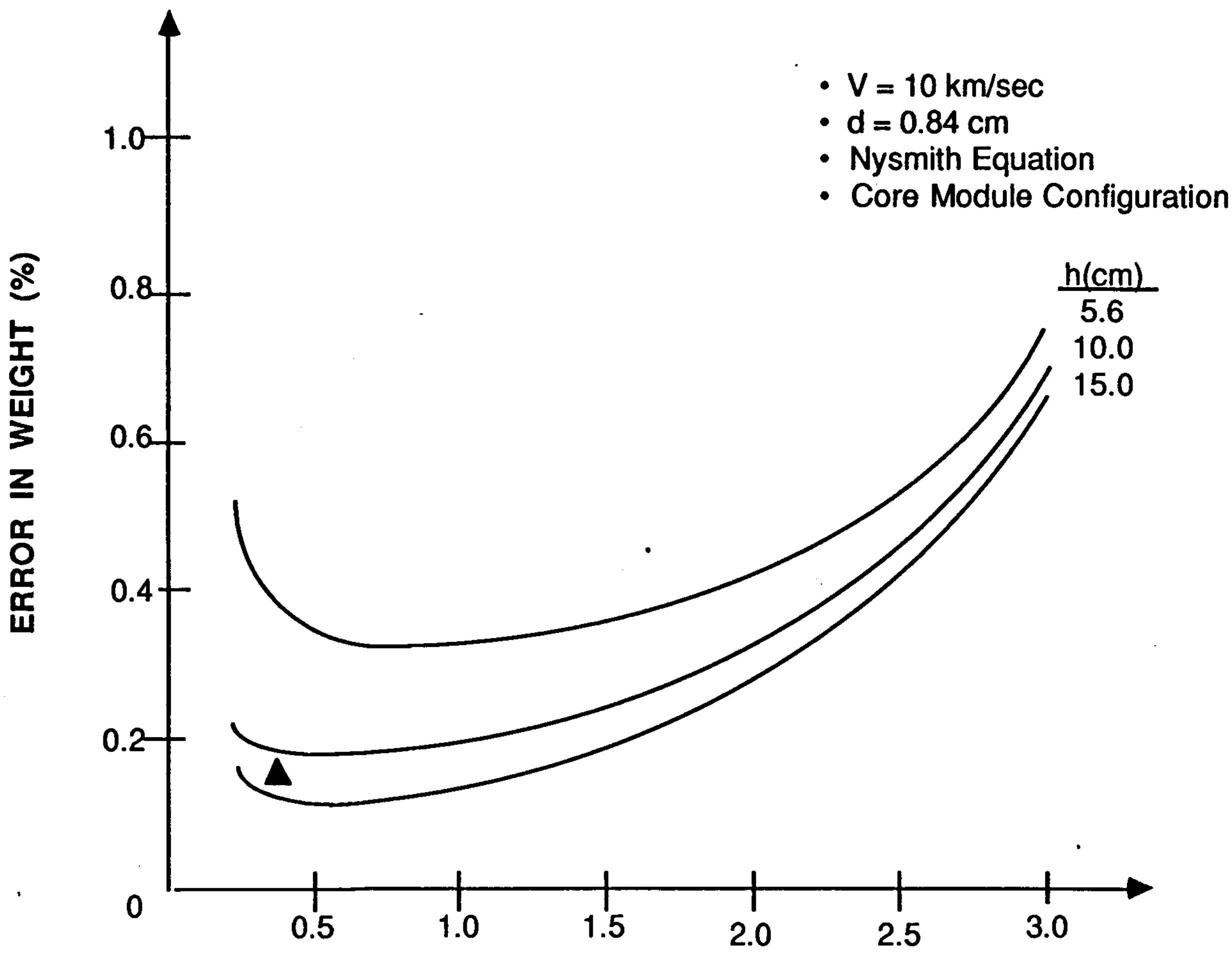
# DESIGN ERROR INDUCED BY REDUCING PROBLEM DEGREE-OF-DIFFICULTY IS NEGLIGIBLE

SHOWN IS THE ERROR IN THE CORE MODULE CONFIGURATION WEIGHT AS A FUNCTION OF BUMPER THICKNESS FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS REPRESENTS THE ERROR INDUCED BY REDUCING THE OPTIMIZATION PROBLEM DEGREE-OF-DIFFICULTY FROM 5 TO 2. THIS ERROR WILL BE NEGLIGIBLE PROVIDED THE BUMPER AND WALL THICKNESSES ARE SMALL IN COMPARISON TO THE MODULE RADIUS. THE MATHEMATICS BEHIND THIS REDUCTION IN DEGREE-OF-DIFFICULTY IS GIVEN IN APPENDIX A.

## DESIGN ERROR INDUCED BY REDUCING PROBLEM DEGREE-OF-DIFFICULTY IS NEGLIGIBLE

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# BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS ARE REFERENCED. THE OPTIMAL DESIGN IS ALMOST EXACTLY THE SAME AS THAT FOUND USING THE IDEALIZED SCENARIO AS THE OBJECTIVE FUNCTION. THIS, COMBINED WITH THE PRECEEDING ERROR SHEET, MAKES IT DESIRABLE TO DETERMINE THE OPTIMAL DESIGN VALUES FROM THE IDEALIZED SCENARIO, AND THEN EVALUATE THE CORE MODULE CONFIGURATION WEIGHT USING THOSE VALUES. NOTE THAT THE BASELINE WEIGHT IS ROUGHLY 3800 Kg, OR 8400 LBS.

BM01-8/31

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# BASELINE DESIGN PARAMETERS

| DESIGN | | PARAMETERS |
|---|---|---|
| $P_o$ | = | 0.97 |
| T | = | 10 YRS |
| $A_d$ | = | 574 $m^2$ |
| $A_m$ | = | 403 $m^2$ |
| Alt | = | 500 km |
| $V_m$ | = | 20 km/sec |
| $V_D$ | = | 10 km/sec |
| $\rho_m$ | = | 0.5 $gm/cm^3$ |
| $\rho_D$ | = | 2.81 $gm/cm^3$ |
| h | = | 10 cm |

NYSMITH EQUATION

**OPTIMAL DESIGN (BALLISTIC LIMIT)**

**BUMPER**

$t_{10}$ = 0.26 cm (0.10 IN)

**WALL**

$t_{20}$ = 0.48 cm (0.19 IN)

WEIGHT ≈ 3800 Kg (8400 lbs)

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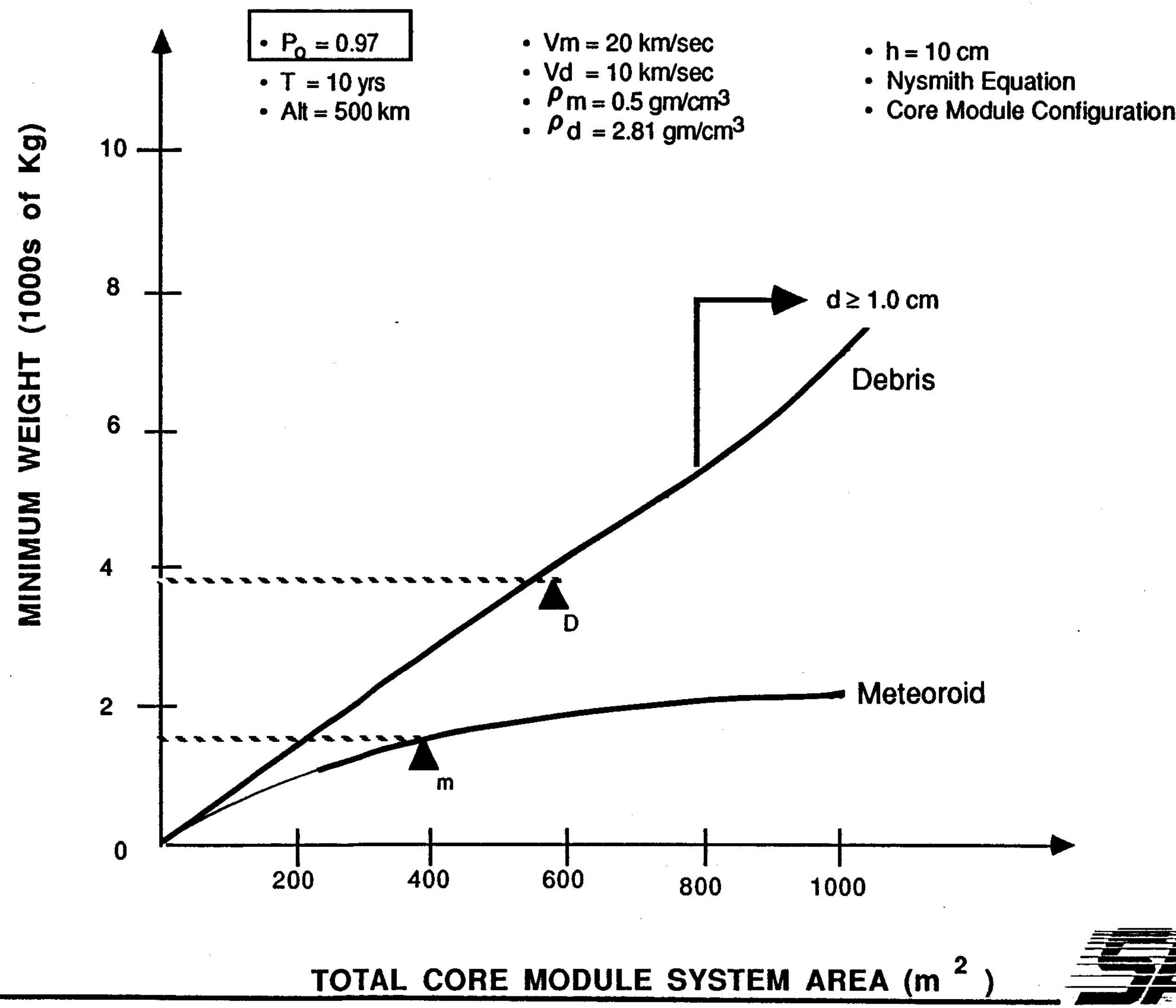
# DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS IS SHOWN. THE DEBRIS ENVIRONMENT DOMINATES THAT OF THE METEOROID FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM.

# DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS



## DEBRIS ENVIRONMENT DRIVES DESPITE $P_0$ REDUCTION

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A $P_0$ OF 0.95 IS SHOWN. ALTHOUGH THIS REDUCTION IN $P_0$ REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

BM30-9/1

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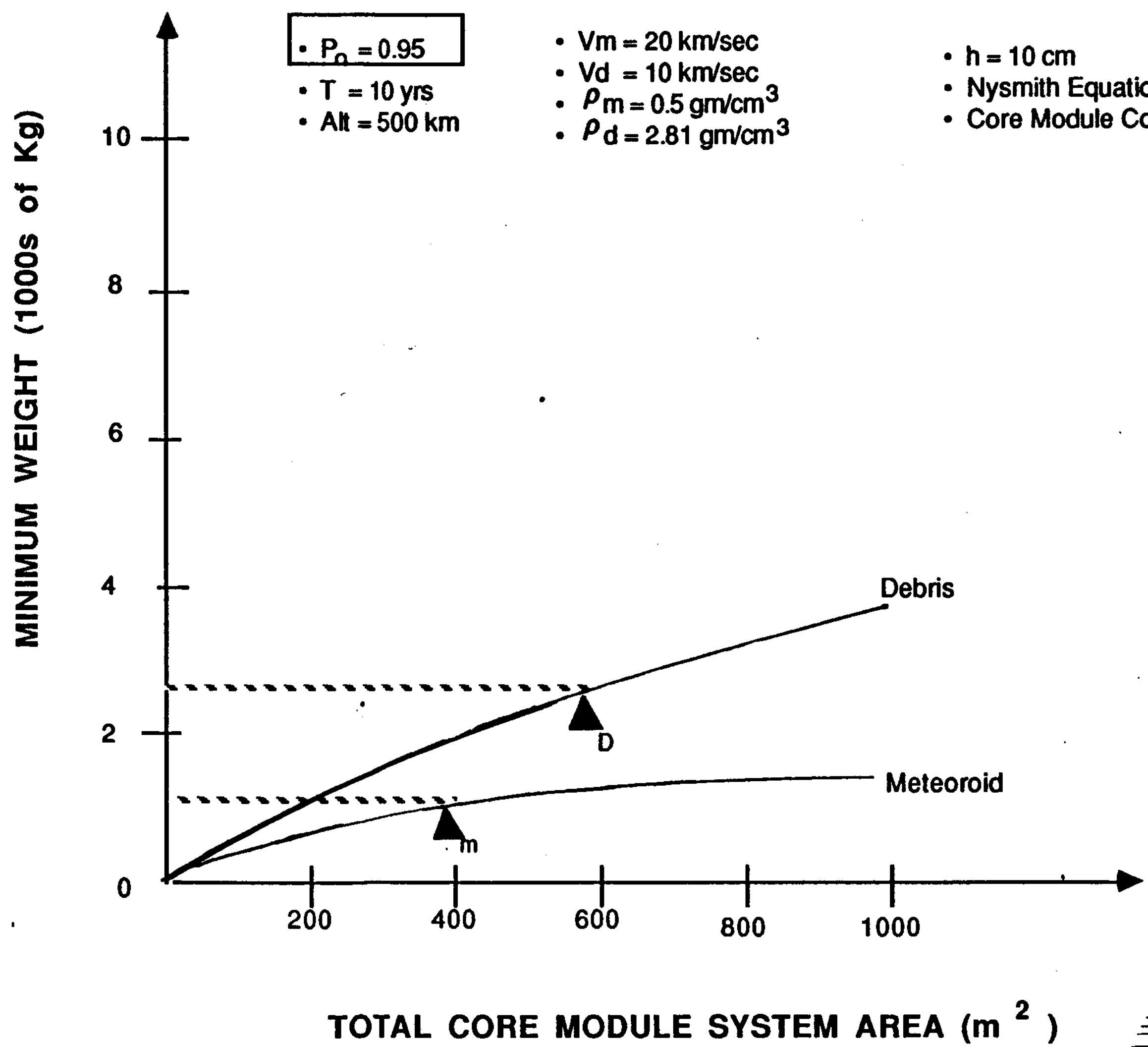
## DEBRIS ENVIRONMENT DRIVES DESPITE $P_o$ REDUCTION

- $P_o = 0.95$
- T = 10 yrs
- Alt = 500 km

- Vm = 20 km/sec
- Vd = 10 km/sec
- $\rho_m = 0.5\ gm/cm^3$
- $\rho_d = 2.81\ gm/cm^3$

- h = 10 cm
- Nysmith Equation
- Core Module Configuration

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## INCREASE IN $P_0$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED.

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A $P_0$ OF 0.99 IS SHOWN. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PARTICLE INDUCED BY SO LARGE A $P_0$ EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

BM13-9/1

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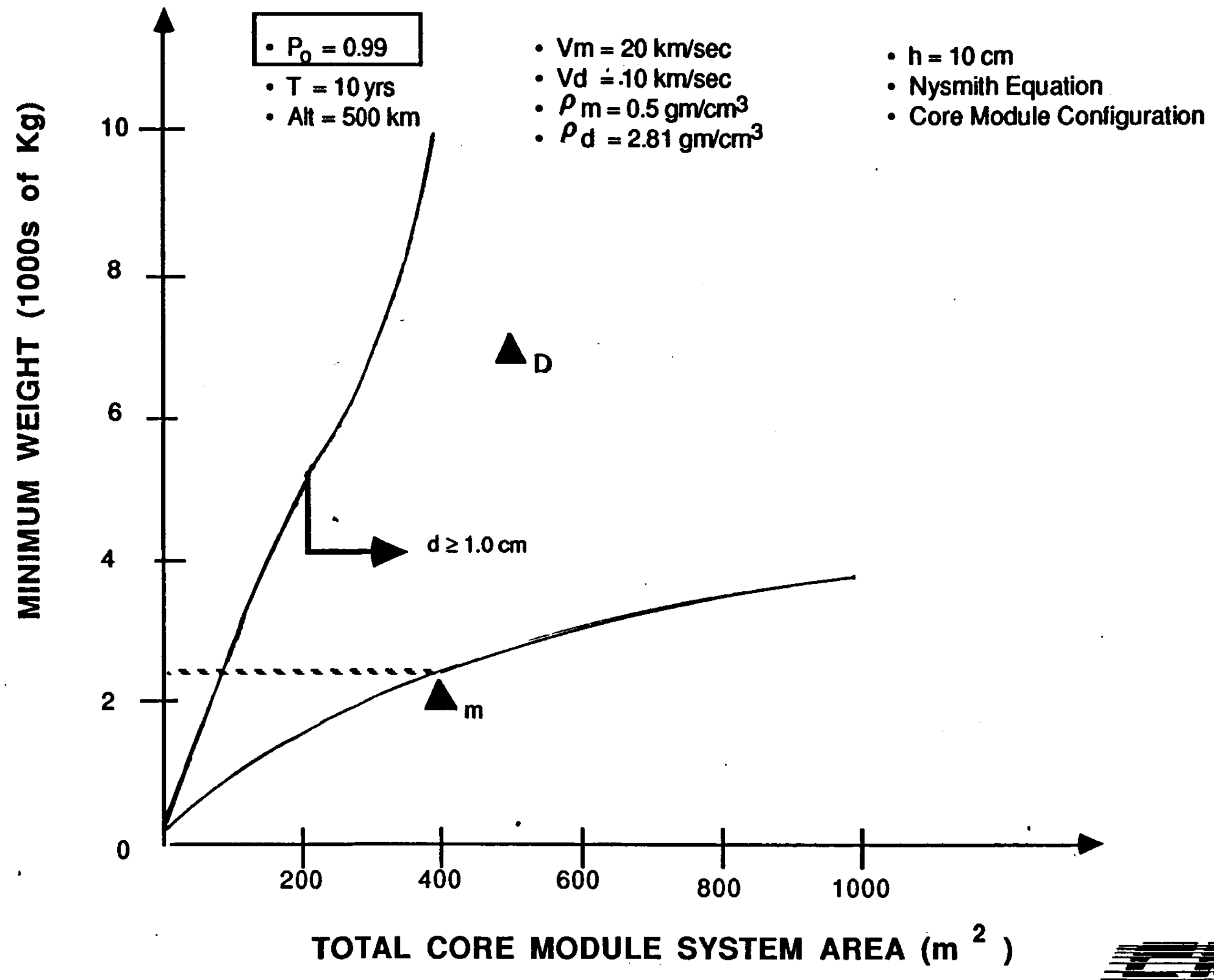
## INCREASE IN $P_o$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED

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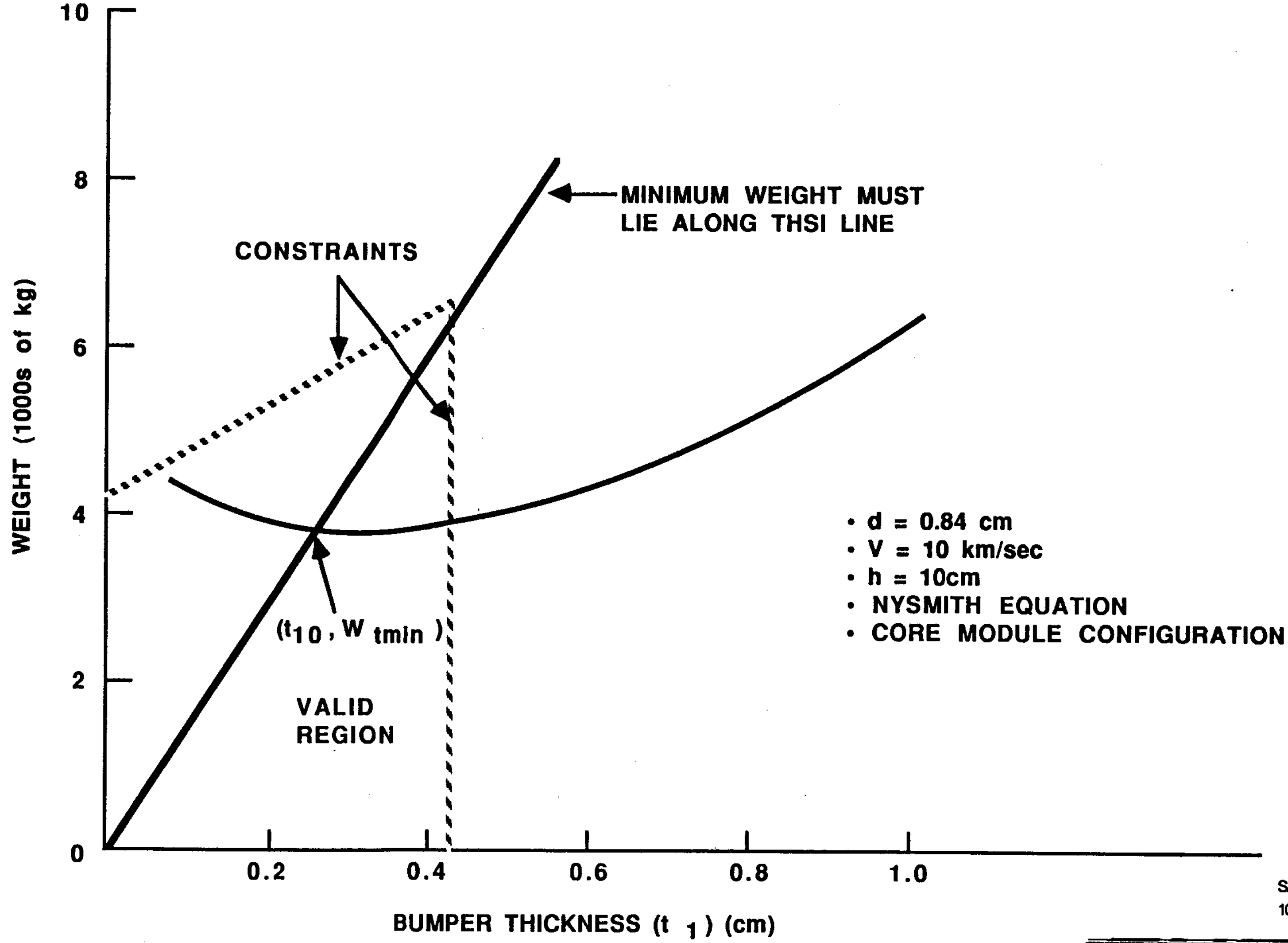
# GP METHOD CONFIRMS THE MINIMUM WEIGHT

SHOWN IS THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP). THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY.

# GP METHOD CONFIRMS THE MINIMUM WEIGHT




SAIC-745
10/12/87

# OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAYOFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARDS THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

BM33-9/1

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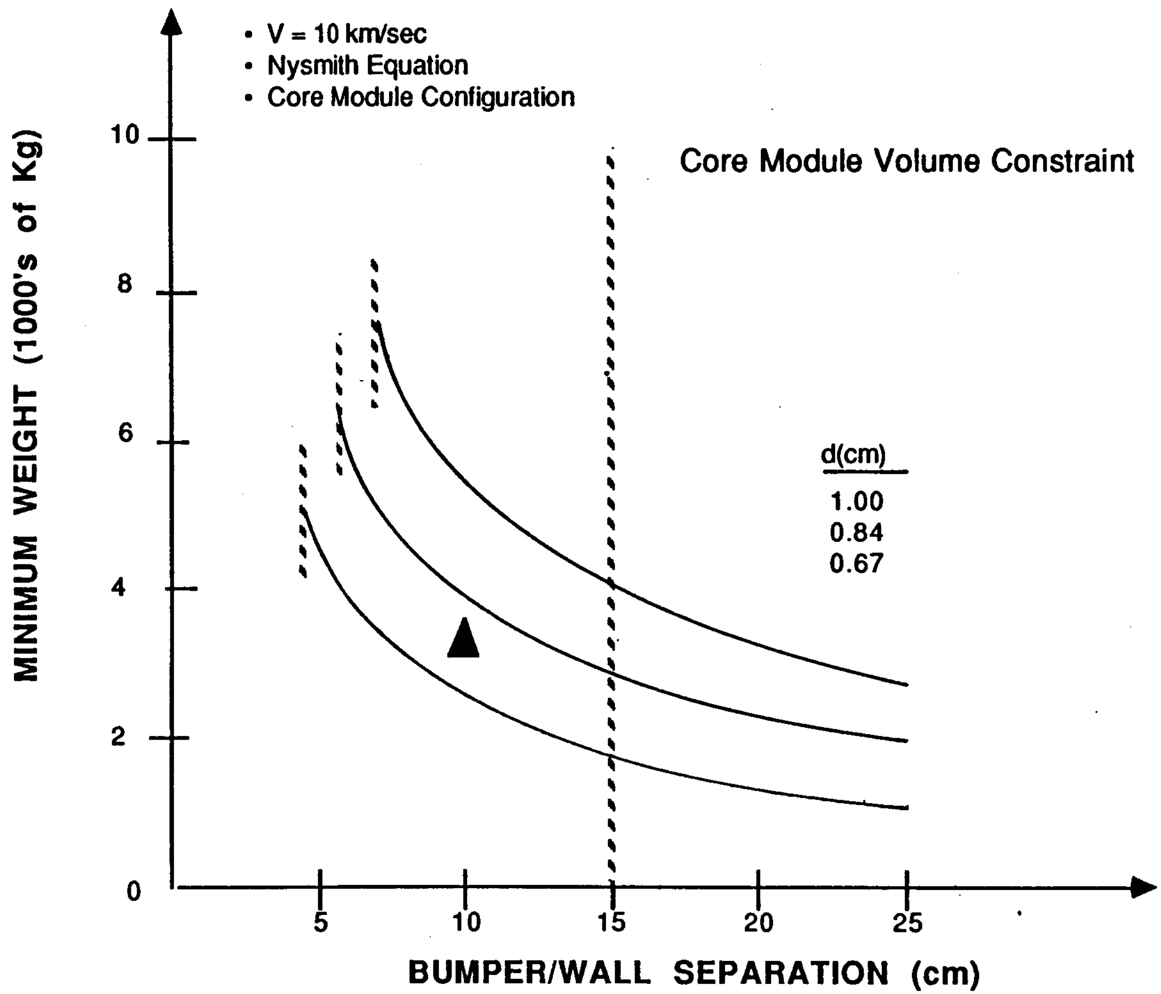
# OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION



# GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.



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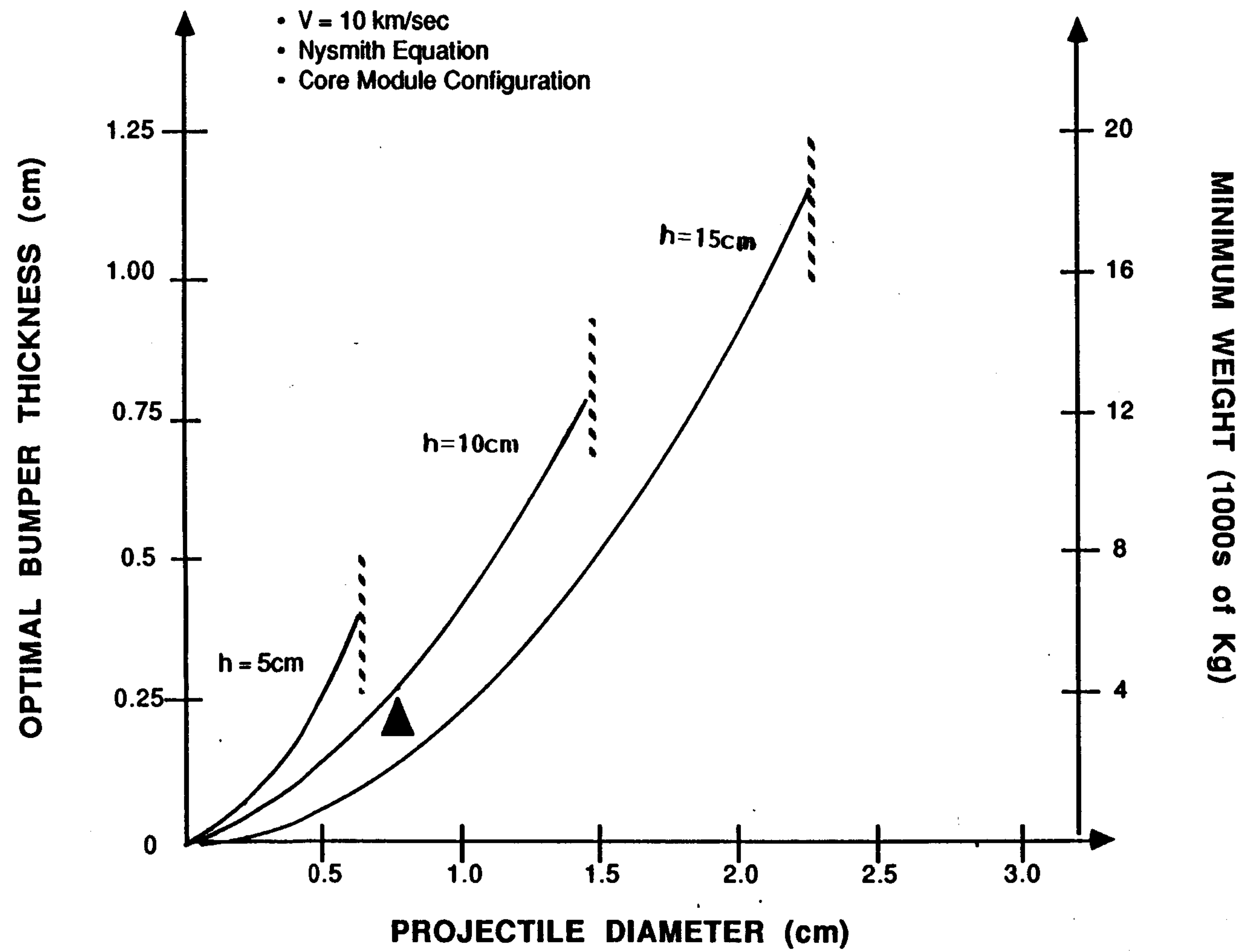
## GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN



# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY.

BM24-9/1

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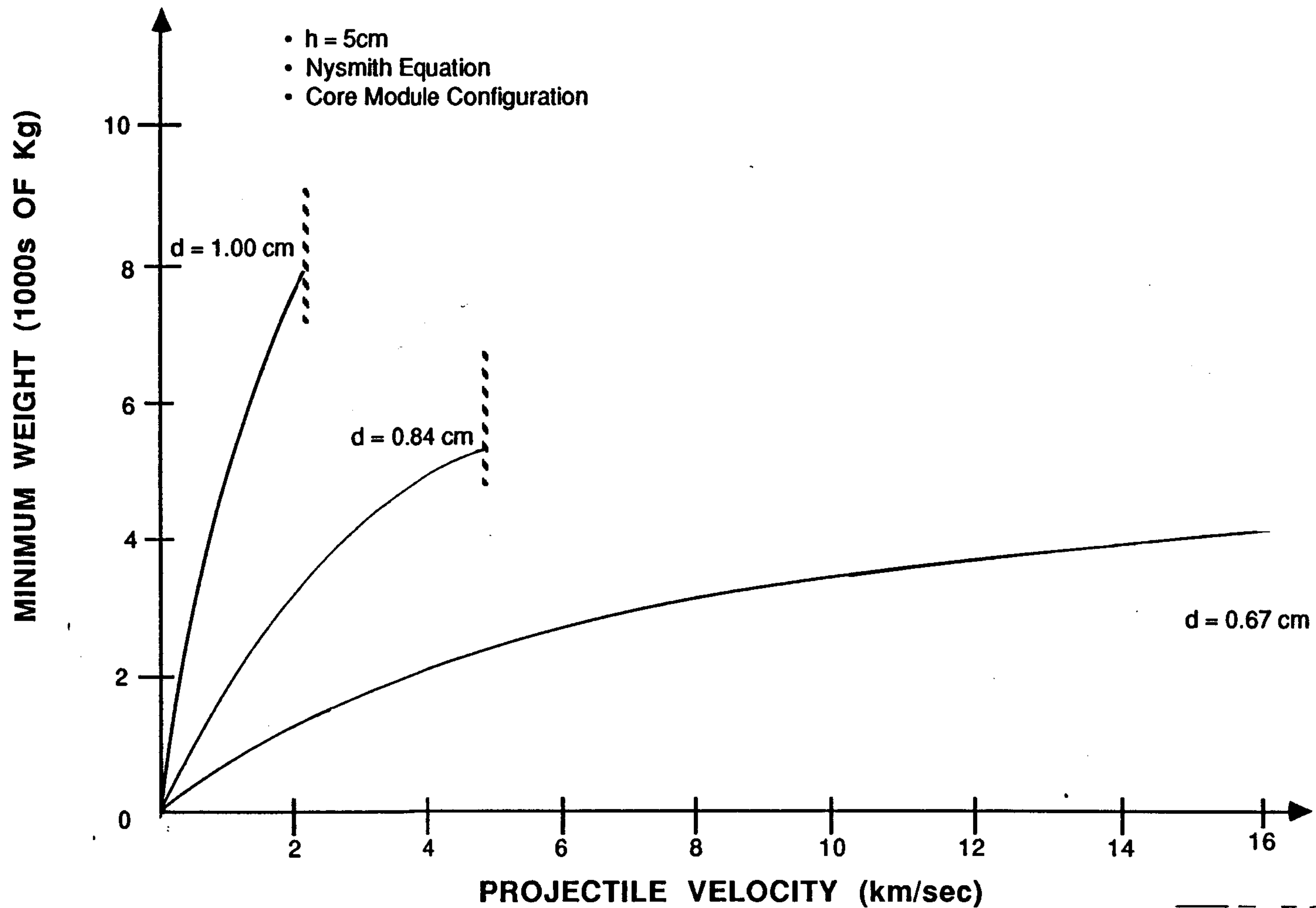
## OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



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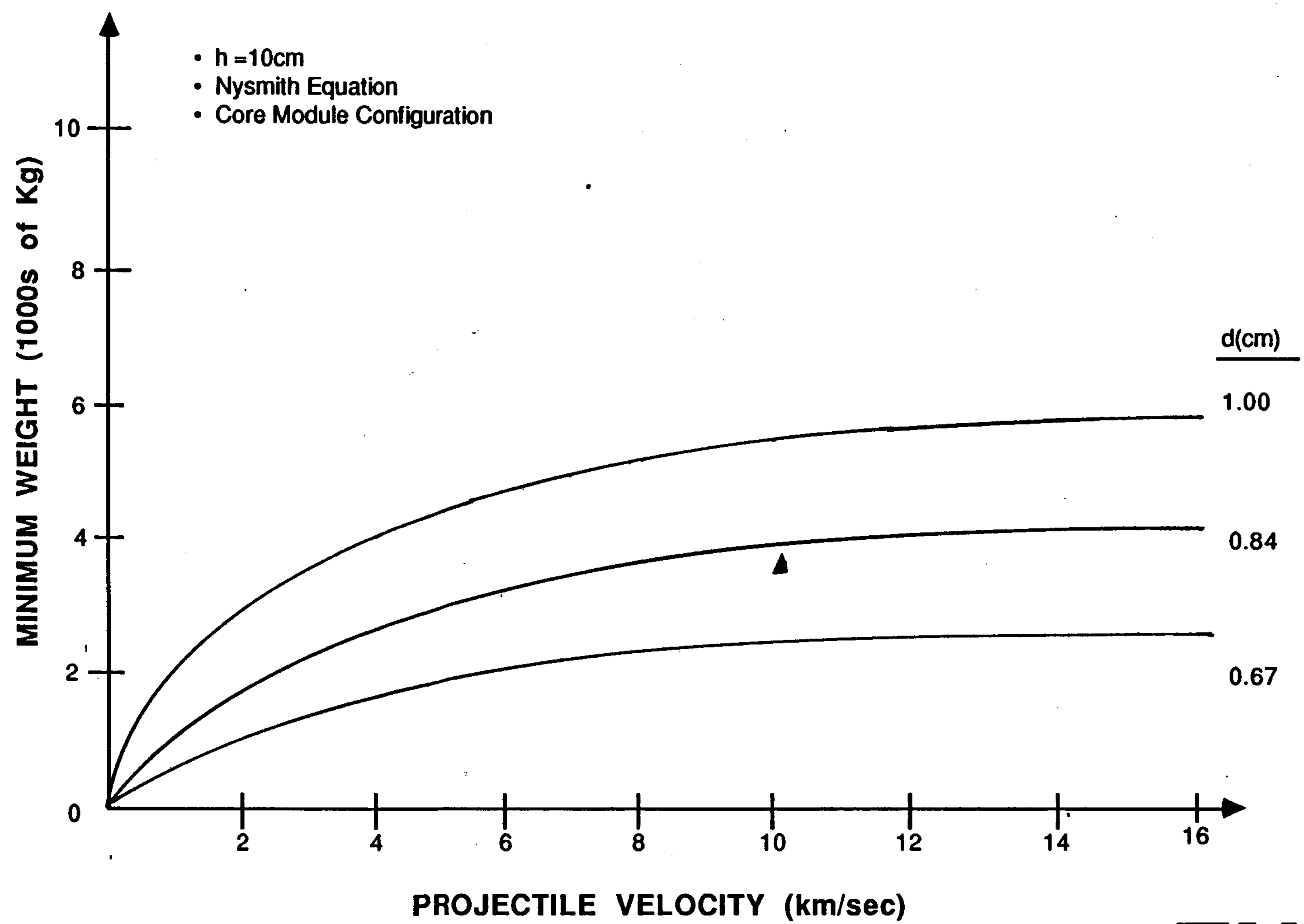
## OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



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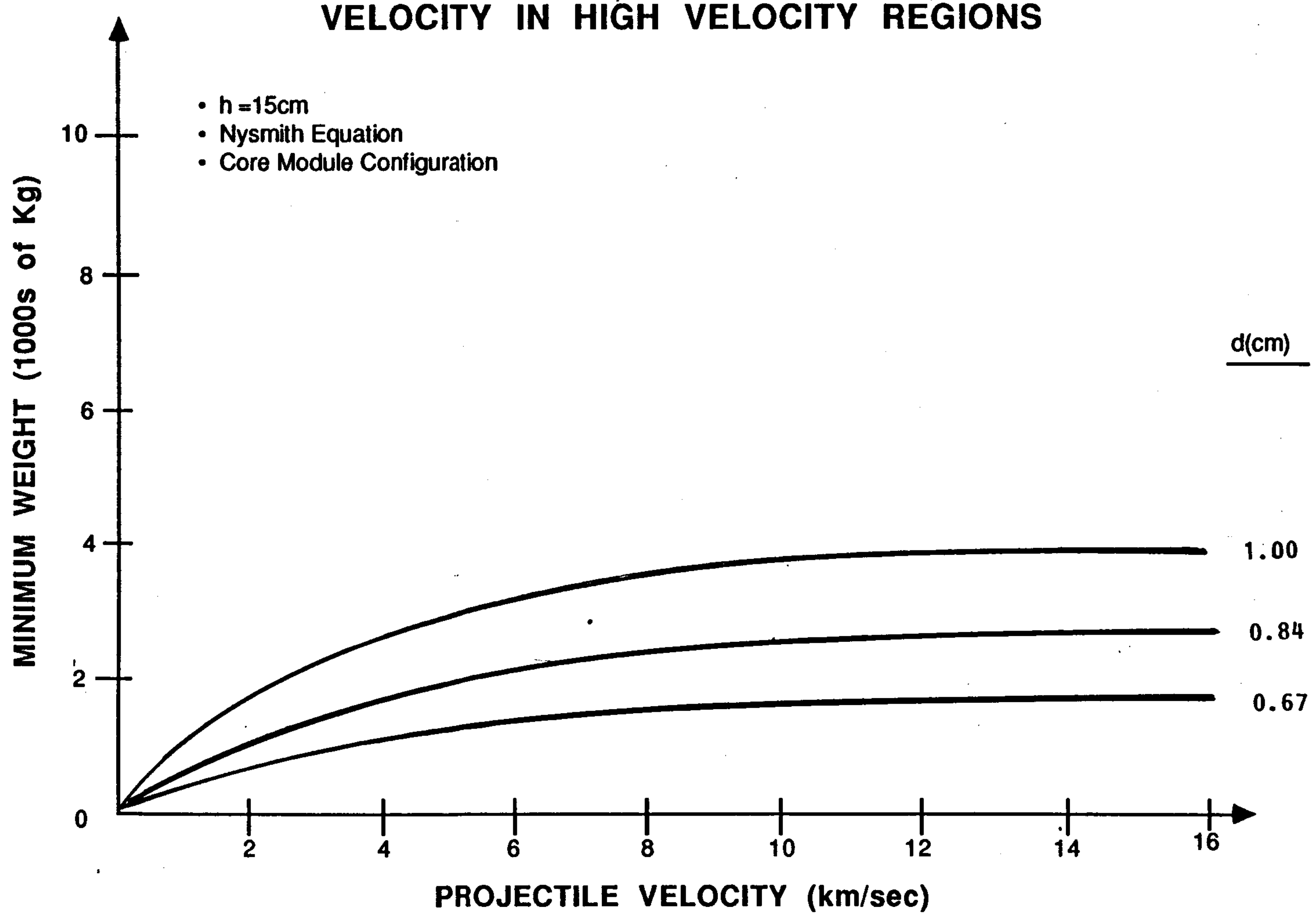
# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

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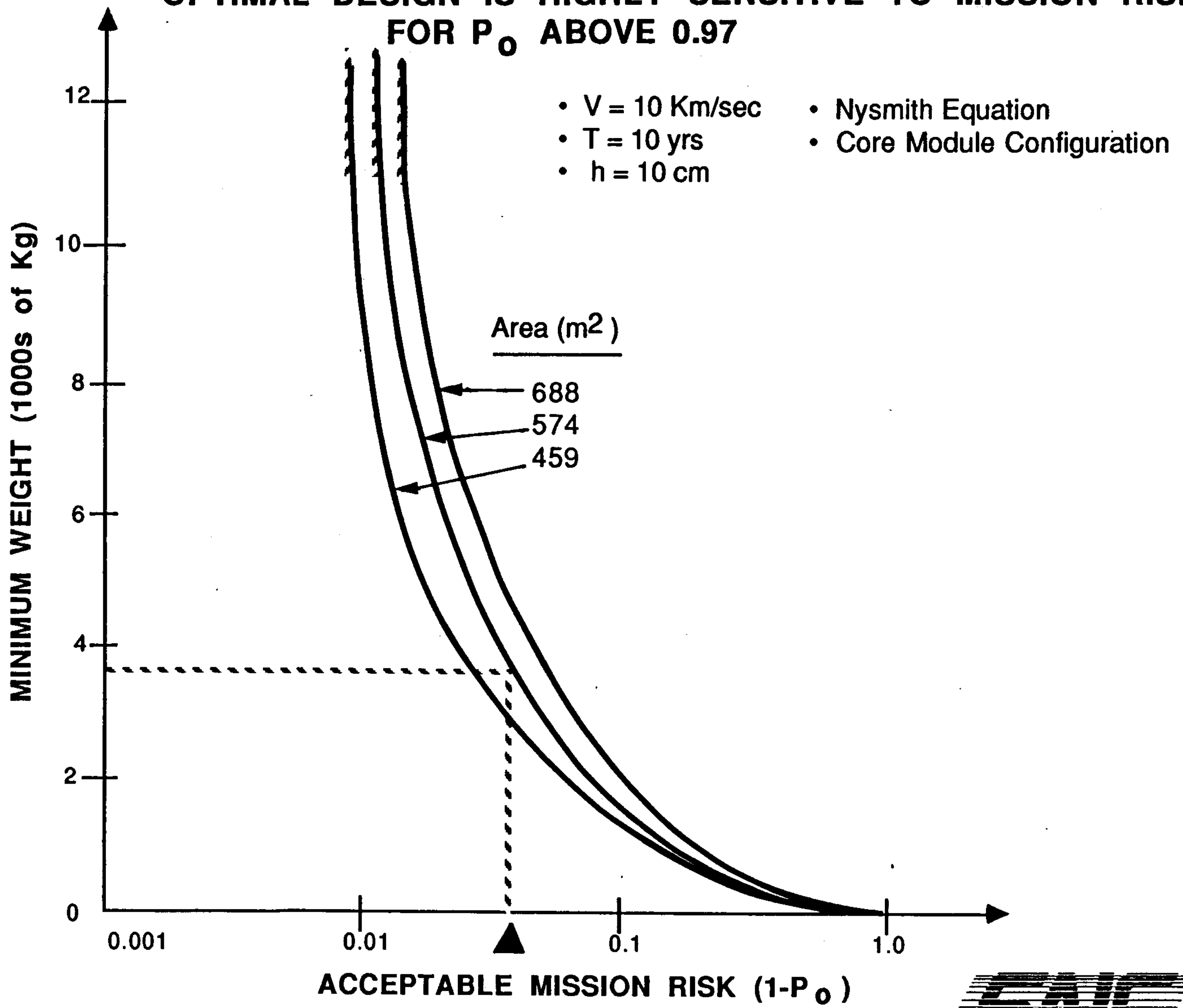
# OPTIMAL DESIGN IS SENSITIVE TO MISSION RISK FOR $P_O$ ABOVE 0.97

THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL SEPARATIONS IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK PLAYS A VERY IMPORTANT ROLE IN DETERMINING THE OPTIMAL DESIGN.

BM36-9/1

SAIC®

## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

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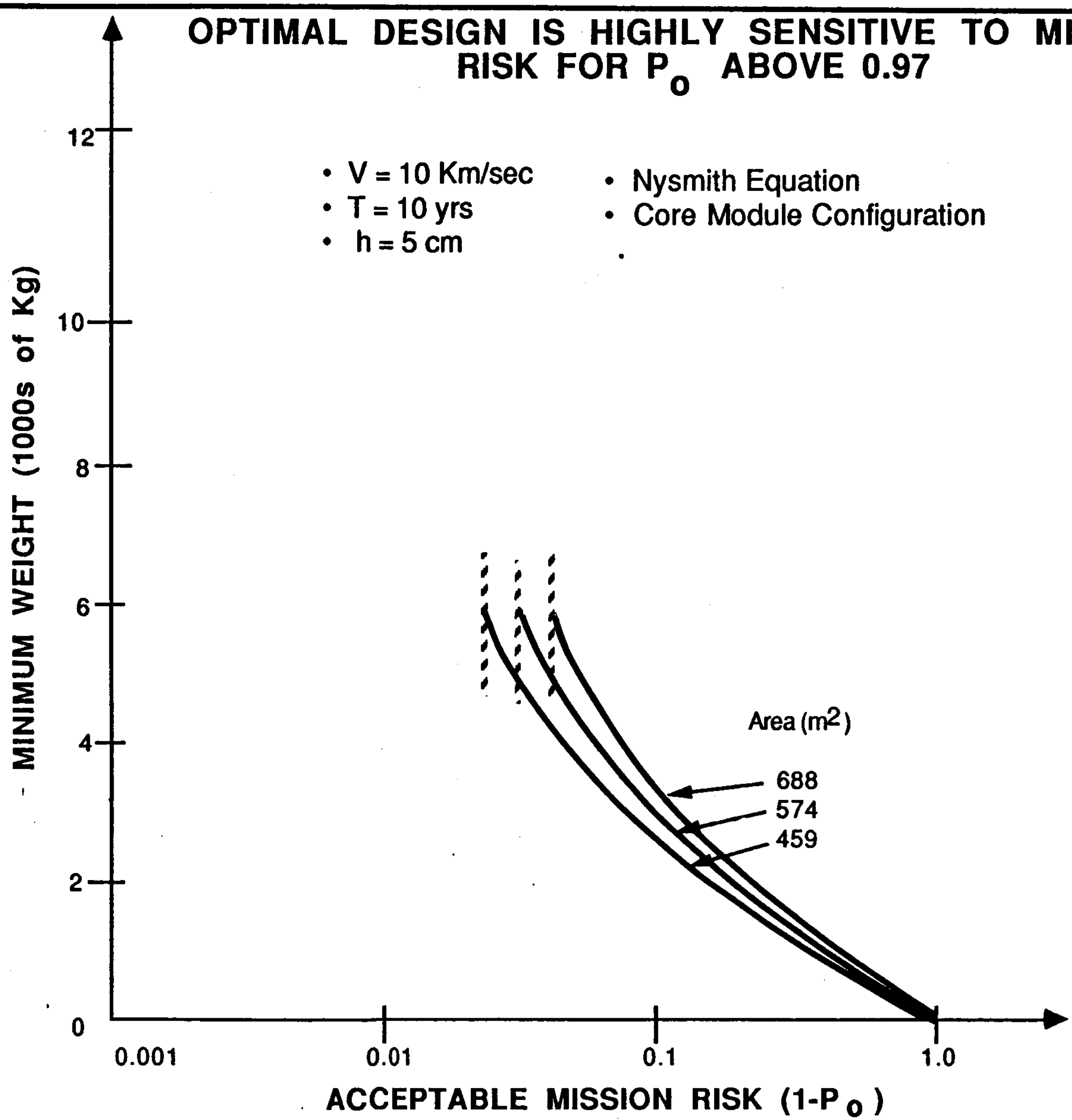
## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97



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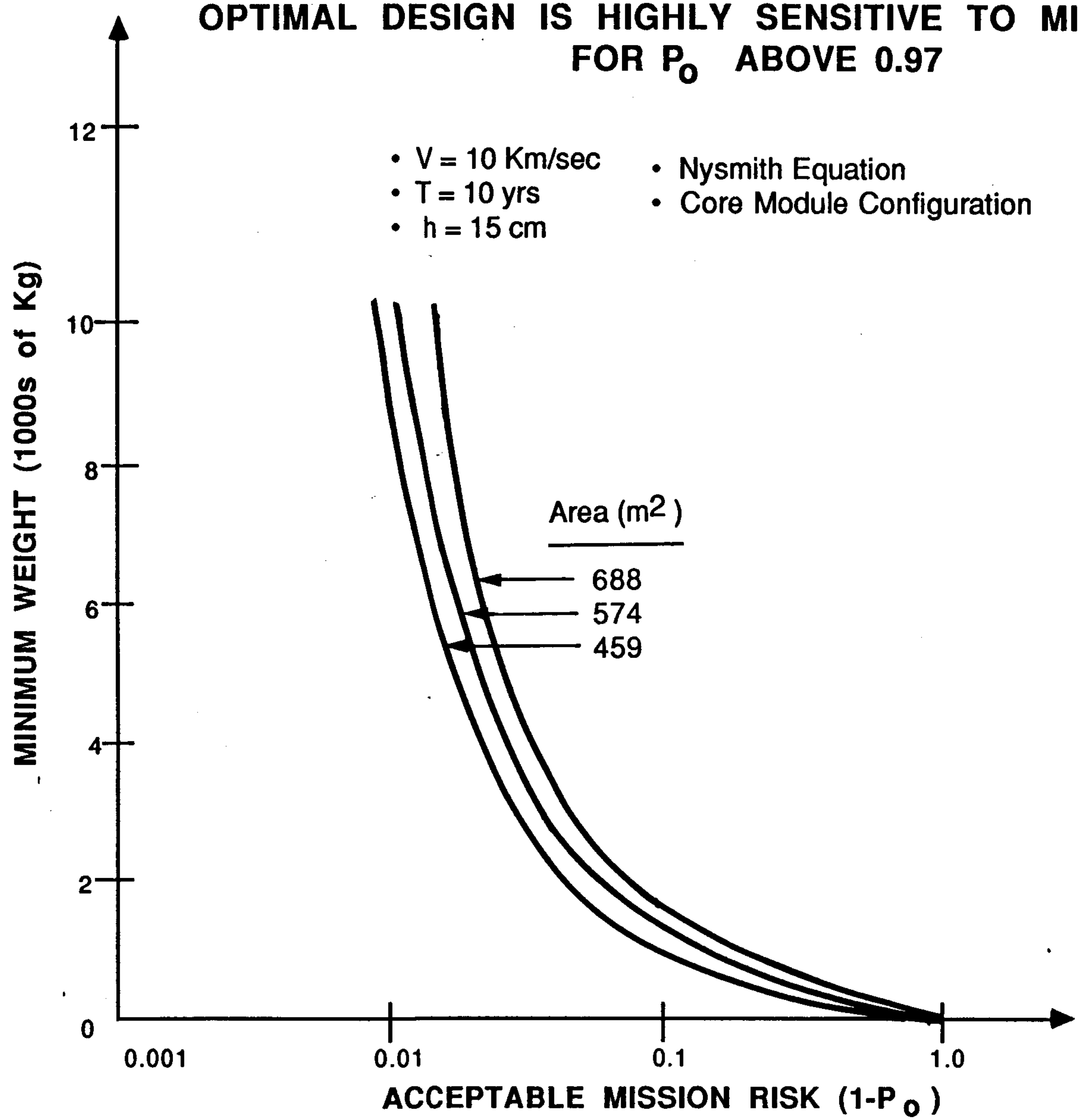
SAIC

## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

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# OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT $P_O$s, THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE.

BM37-9/1

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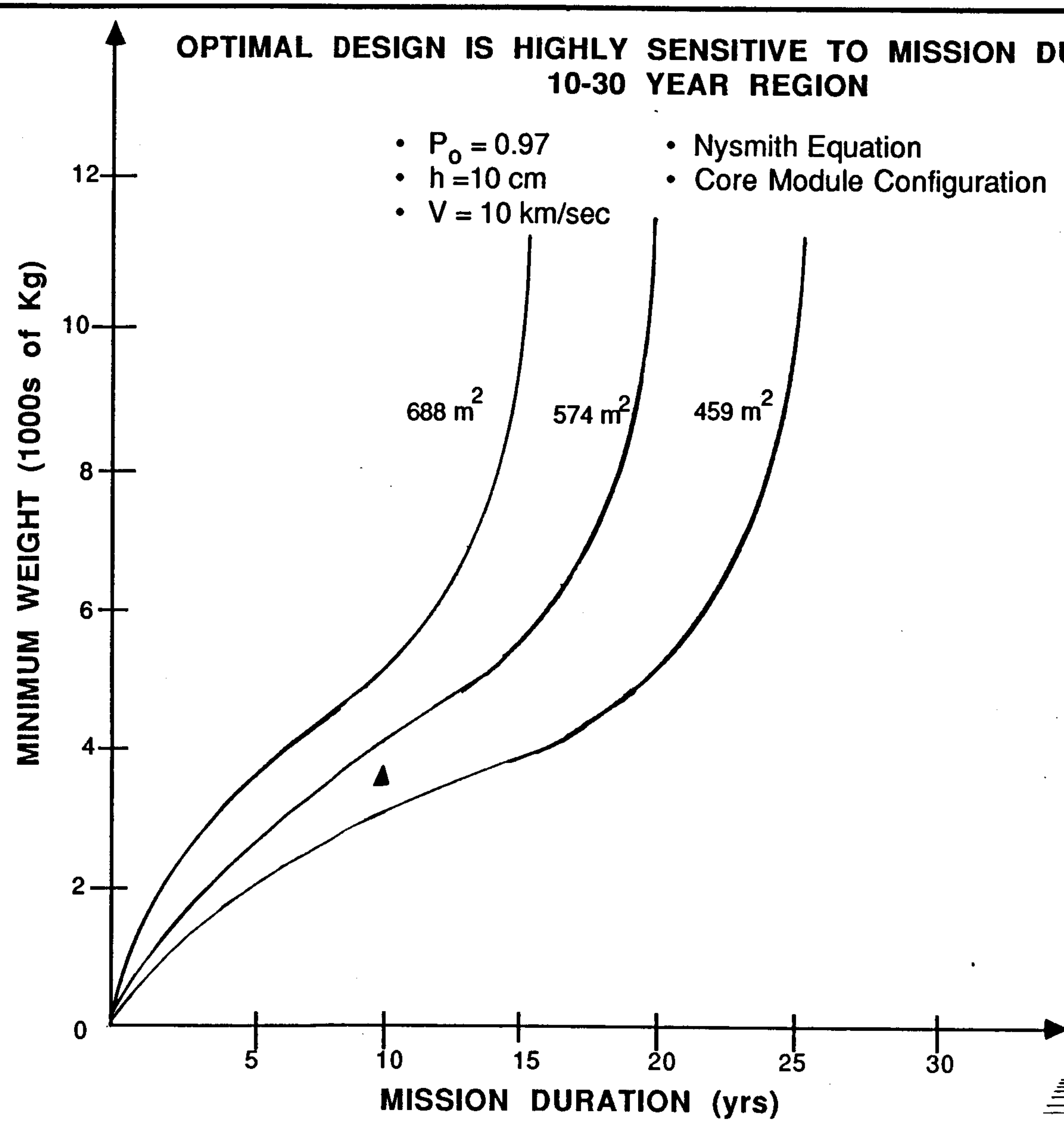
## OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_o = 0.97$
- h =10 cm
- V = 10 km/sec

- Nysmith Equation
- Core Module Configuration

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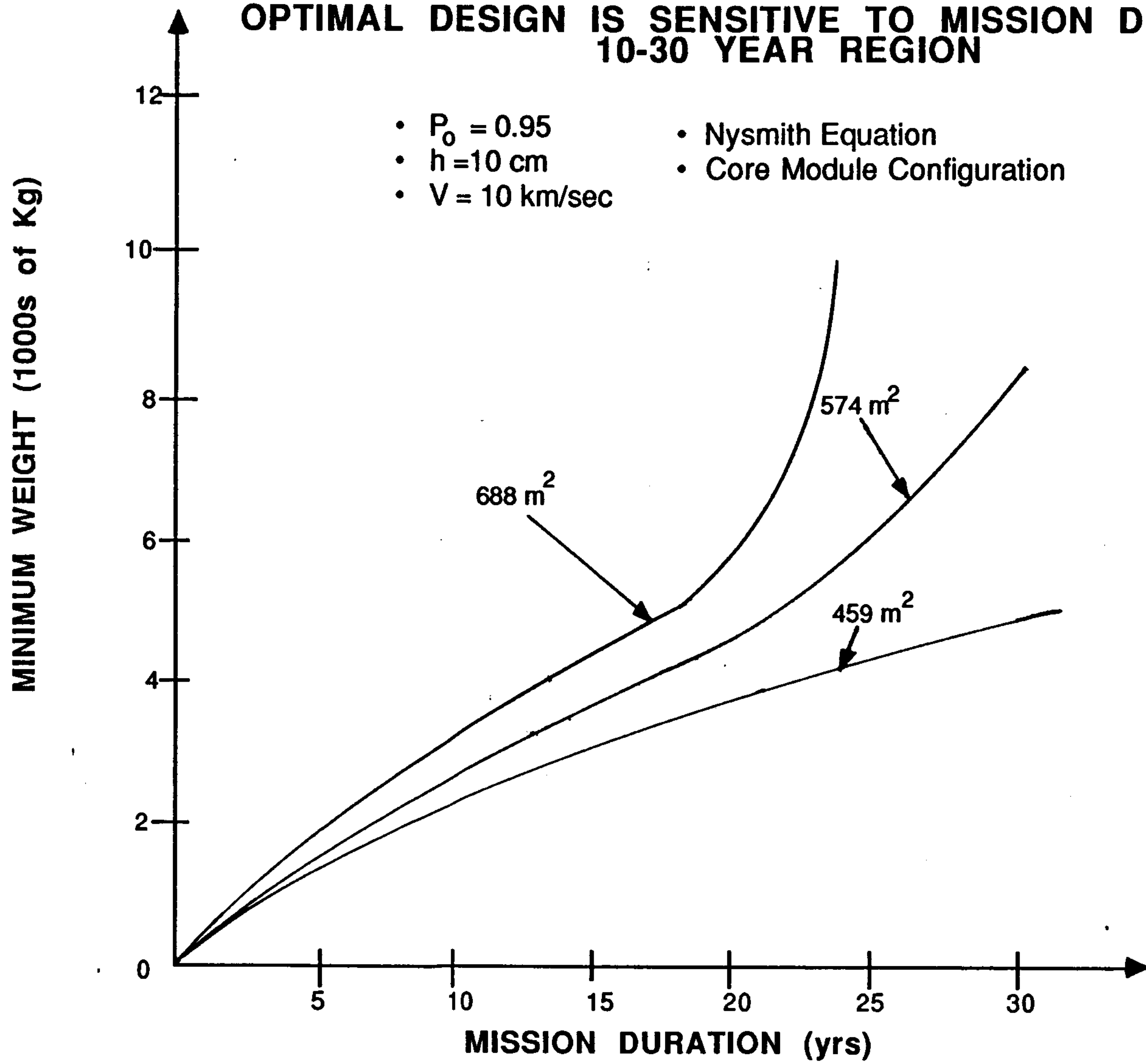
# OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

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# SECTION IV

## GEOMETRIC PROGRAMMING APPLIED TO THE BOEING SUBPREDICTORS.

BM29-8/21

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# WHAT YOU WILL SEE IN SECTION IV

- DEFINITIONS AND BASELINE DESIGN PARAMETERS FOR THE THREE BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

BM4 10/13

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# THE PEN4 PREDICTOR

THE PEN4 PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER/WALL SEPARATION. ALSO, NOTE THAT THE PEN4 PREDICTOR IS VELOCITY CONSTRAINED. THIS PREDICTOR WAS OPTIMIZED USING A SEARCH TECHNIQUE, WITH THE VELOCITY CONSTRAINT CHECKED EXTERNALLY TO THE OPTIMIZATION.

# THE PEN4 PREDICTOR

$$t_2 = 1.67 \left(\frac{C_1 \rho_p}{2\ Sy_2}\right)^{.31} \left(\frac{.281\ D\ \rho_p}{\rho_2}\right)^{1/3} \cos(\theta)$$

$$C_1 = \frac{a-b}{c+d}$$

$$a = 1.33 V^2 Rp^2 \rho_p$$

$$b = 8\ Sy_1 t_1 e^{-3.125 \times 10^{-4} V / \cos(\theta)}$$

$$c = 1.33\ Rp^2 \rho_p$$

$$d = Rp t_1 \rho_1 / \cos(\theta)$$

Valid for $V \leq V_f + 4000$, where

$$V_f = \begin{cases} 4100, & \text{if } t_1/D \leq 0.4 \\ 4986\,(t_1/D)^{0.21}, & \text{if } t_1/D > 0.4 \end{cases}$$

BMO1-8/21

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# THE PEN4 PREDICTOR (CONTINUED)

$V$ = particle velocity, ft/sec

$t_1$ = bumper thickness, ft

$t_2$ = wall thickness, ft

$D$ = particle diameter, ft

$R_p$ = particle radius, ft

$\rho_p$ = projectile density, slugs/$ft^3$

$\rho_1$ = bumper density, slugs/$ft^3$

$\rho_2$ = wall density, slugs/$ft^3$

$\theta$ = impact angle from the normal, degrees

$Sy_1$ = bumper yield strength, lb/$ft^2$

$Sy_2$ = wall yield strength, lb/$ft^2$

No bumper/wall separation dependency

BM08-8/21

SAIC

# BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE PEN4 PREDICTOR ARE SHOWN. SINCE THIS PREDICTOR IS NOT VALID FOR A PROJECTILE VELOCITY OF 10 KM/SEC, NO OPTIMAL DESIGN IS INDUCED.

# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

| | | |
|---|---|---|
| $P_o$ | = 0.97 | (PROBABILITY OF NO PENETRATION) |
| $T$ | = 10 yrs | (MISSION DURATION) |
| $A_d$ | = 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = 403 $m^2$ | (METEOROID AREA) |
| Alt | = 500 km | (AVERAGE ALTITUDE) |
| $V_m$ | = 20 km/sec | (AVERAGE METEOROID VELOCITY) |
| $V_D$ | = 10 km/sec | (AVERAGE DEBRIS VELOCITY) |
| $\rho_m$ | = 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| $\rho_1$ | = 2.81 $gm/cm^3$ | |
| $\rho_2$ | = 2.81 $gm/cm^3$ | |
| $\theta$ | = 0 degrees | |
| $Sy_1$ | = 7344000 $lb/ft^2$ (51 Ksl) | |
| $Sy_2$ | = $Sy_1$ | |

→

## OPTIMAL DESIGN (BALLISTIC LIMIT)

INVALID

BM03-8/21

SAIC

# THE BURCH PREDICTOR
# (NORMAL IMPACT)

THE BURCH PREDICTOR FOR NORMAL IMPACTS IS SHOWN WITH PARAMETER DEFINITION. NOTE THAT THERE IS NO DEPENDENCE ON PROJECTILE OR WALL MATERIAL PROPERTIES.

# THE BURCH PREDICTOR (NORMAL IMPACT)

$$t_2 = \left(\frac{F_1 D}{N}\right)^{1.71} \left(\frac{C}{V}\right)^{2.29} \Big/ S^{0.71}, \text{ where}$$

$F_1$ = $2.42\,(t_1/D)^{-0.33} + 4.26\,(t_1/D)^{0.33} - 4.18$

$C$ = speed of sound in shield, ft/sec = $\sqrt{E_1/\rho_1}$

$E_1$ = Youngs Modulus of Elasticity for bumper, lb/ft-sec$^2$

$\rho_1$ = bumper density, lb/ft$^3$

$V$ = projectile velocity, ft/sec

$S$ = spacing, inches

$D$ = projectile diameter, inches

$t_1$ = bumper thickness, inches

$t_2$ = wall thickness, inches

$N$ = number of plates to penetrate after 1st bumper

No projectile material property dependency
No wall material property dependency

BM09-8/21

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# THE MODIFIED BURCH PREDICTOR

THE MODIFIED BURCH PREDICTOR IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR IS A POSYNOMIAL, WHICH ALLOWS IT TO BE OPTIMIZED GLOBALLY USING GEOMETRIC PROGRAMMING.

BM17-8/21

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# THE MODIFIED BURCH PREDICTOR

**SAME AS THE BURCH PREDICTOR EXCEPT:**

$$F_1 = 2.8\ (t_1/D)^{0.57} + 1.58\ (t_1/D)^{-0.57}$$

BM10-8/21

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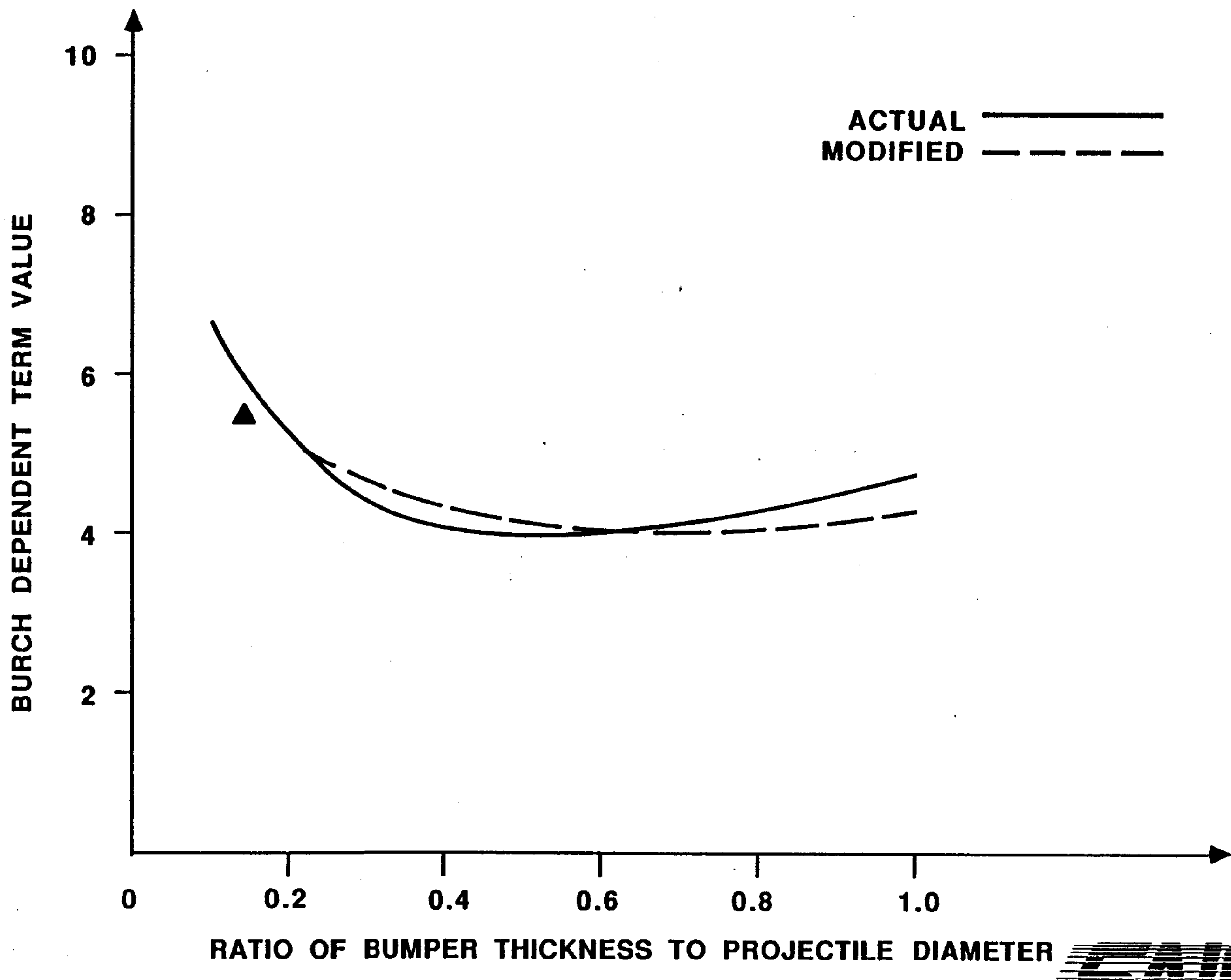
## MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS

SHOWN IS THE BURCH DEPENDENT TERM VALUE (PROPORTIONAL TO THE WALL THICKNESS) AS A FUNCTION OF THE RATIO OF THE BUMPER THICKNESS TO PROJECTILE DIAMETER FOR THE BURCH AND MODIFIED BURCH PREDICTORS. USING THE MODIFIED BURCH PREDICTOR ALLOWS THE DESIGNER TO APPLY THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE, THUS REDUCING COMPUTER USAGE AND GUARANTEEING GLOBAL DESIGN OPTIMIZATION, ALL FOR A SMALL PRICE IN TERMS OF DESIGN ERROR.

# MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS




SAIC-658F
8/4/87

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# BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE MODIFIED BURCH PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 26% BUMPER, 74% WALL.

BM03A-9/9

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# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

| | | |
|---|---|---|
| $P_o$ | = 0.97 | (PROBABILITY OF NO PENETRATION) |
| $T$ | = 10 yrs | (MISSION DURATION) |
| $A_d$ | = 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = 403 $m^2$ | (METEOROID AREA) |
| Alt | = 500 km | (AVERAGE ALTITUDE) |
| $V_m$ | = 20 km/sec | (AVERAGE METEOROID VELOCITY) |
| $V_D$ | = 10 km/sec | (AVERAGE DEBRIS VELOCITY) |
| $\rho_m$ | = 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| S | = 10 cm | (BUMPER/WALL SEPARATION) |
| $E_1$ | = $7.239 \times 10^{11}$ $gm/cm\text{-}sec^2$ | |
| $\rho_1$ | = 2.81 $gm/cm^3$ | |

## OPTIMAL DESIGN (BALLISTIC LIMIT)

**BUMPER**

$t_{10}$ = 0.09cm (0.04 in)

**WALL**

$t_{20}$ = 0.25cm (0.10 in)

CMC weight = 1775 Kg (3905 lb)

BM04-8/21

SAIC™

# THE WILKINSON PREDICTOR

THE WILKINSON PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR FORMS A COMPLETE SET OF PARAMETERS. ALSO, NOTE THAT THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL. THE WILKINSON PREDICTOR WAS OPTIMIZED USING GEOMETRIC PROGRAMMING.



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# THE WILKINSON PREDICTOR

$$t_2 = 0.364\ D^4 \rho_p^2 V_n / (L_2 S^2 \rho_1 t_1 \rho_2)\ ,\ \text{if}\ \frac{D \rho_p}{\rho_1 t_1} > 1.$$

$$t_2 = 0.364\ D^3 \rho_p V_n / (L_2 S^2 \rho_2),\ \text{if}\ \frac{D \rho_p}{\rho_1 t_1} \leq 1.$$

$\rho_p$ = projectile density, $gm/cm^3$

$D$ = projectile diameter, cm

$V_n$ = normal component of velocity vector, km/sec

$S$ = spacing, cm

$\rho_1$ = bumper density, $gm/cm^3$

$\rho_2$ = wall density, $gm/cm^3$

$L_2$ = wall material constant

$t_1$ = bumper thickness, cm

$t_2$ = wall thickness, cm

BM11-8/21

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# BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE WILKINSON PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 50% WALL, 50% BUMPER.



SAIC

# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

| | | |
|---|---|---|
| $P_o$ | = 0.97 | (PROBABILITY OF NO PENETRATION) |
| $T$ | = 10 yrs | (MISSION DURATION) |
| $A_d$ | = 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = 403 $m^2$ | (METEOROID AREA) |
| Alt | = 500 km | (AVERAGE ALTITUDE) |
| $V_m$ | = 20 km/sec | (AVERAGE METEOROID VELOCITY) |
| $V_D$ | = 10 km/sec | (AVERAGE DEBRIS VELOCITY) |
| $\rho_m$ | = 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| S | = 10 cm | (BUMPER/WALL SEPARATION) |
| $\rho_1$ | = 2.81 $gm/cm^3$ | |
| $\rho_2$ | = $\rho_1$ | |
| $L_2$ | = 0.401 | |

## OPTIMAL DESIGN (BALLISTIC LIMIT)

**BUMPER**

$t_{10}$ = 0.21cm (0.08 in)

**WALL**

$t_{20}$ = 0.21cm (0.08 in)

CMC weight = 2209 Kg (4860 lb)

BM05-8/21

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# DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH

THE EFFECT OF CHANGES IN THE CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID CASES FOR THE MODIFIED BURCH SUBPREDICTOR IS SHOWN. AGAIN, THE DEBRIS ENVIROMENT DOMINATES THAT OF THE METEOROID.

BM04-8/5

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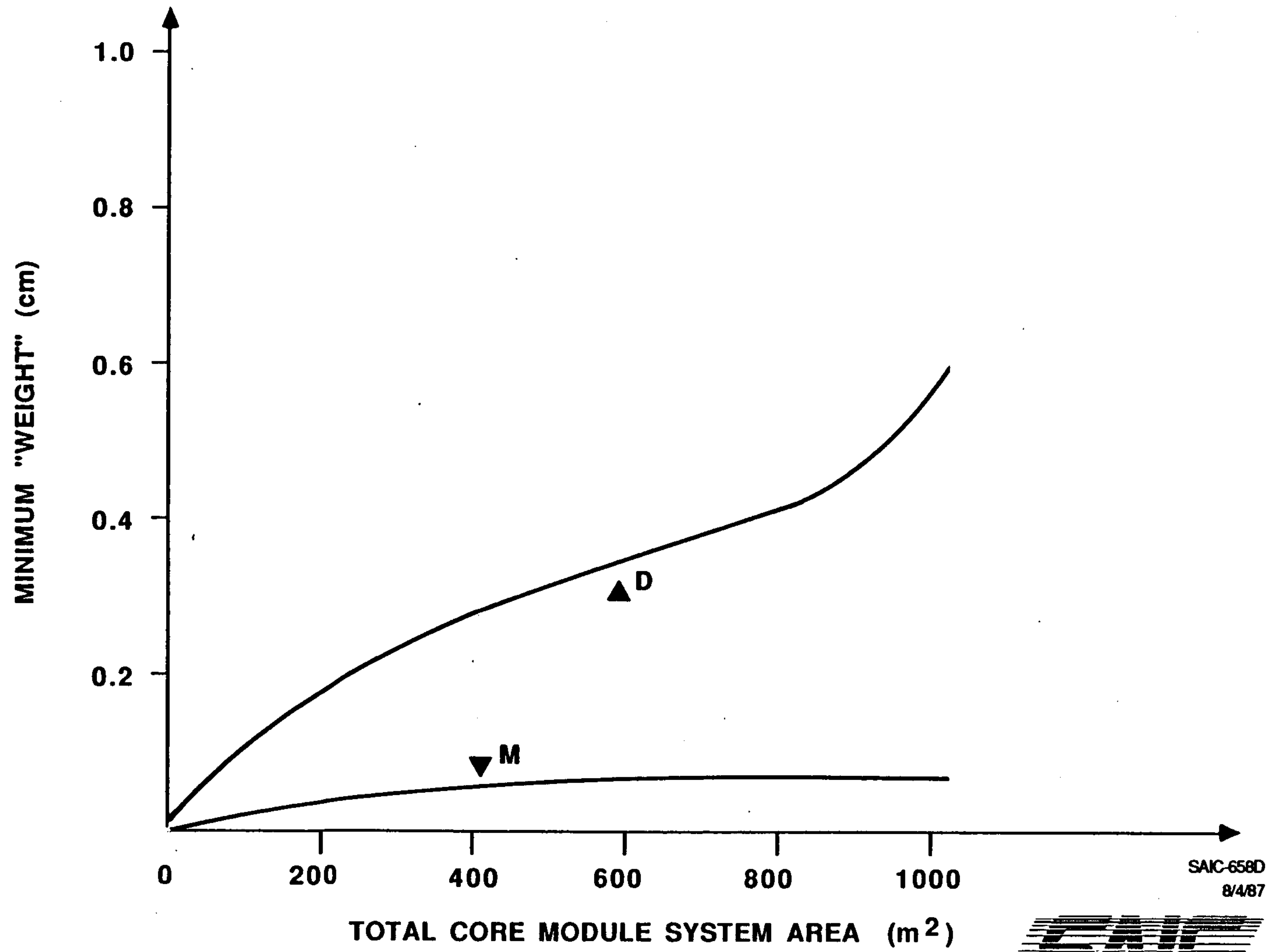
# DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH




SAIC-658D
8/4/87

## DEBRIS ENVIRONMENT DRIVES FOR WILKINSON

SHOWN IS THE EFFECT OF CHANGES IN CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE WILKINSON SUBPREDICTOR. THE DOMINANCE OF THE DEBRIS SCENARIO OVER THE METEOROID SCENARIO IS MORE STRIKING FOR WILKINSON THAN NYSMITH BECAUSE THE WILKINSON PREDICTOR ACCOUNTS FOR PROJECTILE DENSITY AND THE NYSMITH DOES NOT.



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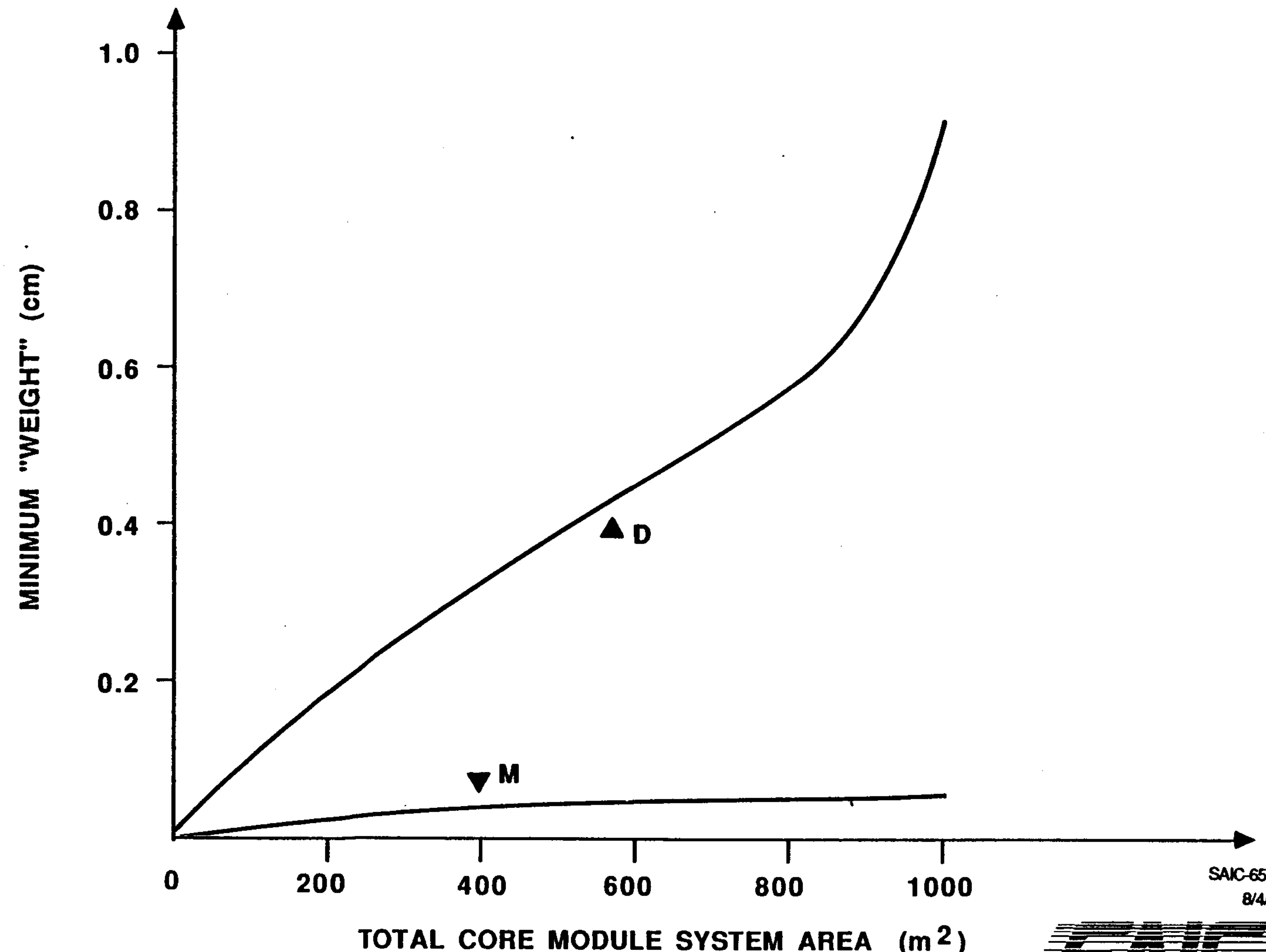
# DEBRIS ENVIRONMENT DRIVES FOR WILKINSON




SAIC-658D
8/4/87

# VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS

THE DESIGN SENSITIVITY TO PROJECTILE VELOCITY FOR THE THREE BOEING SUBPREDICTORS IS SHOWN. BOTH THE PEN4 AND WILKINSON SUBPREDICTORS SHOW OPTIMAL DESIGN INCREASING WITH INCREASING VELOCITY, ALTHOUGH THE PEN4 CURVE IS CONVEX, WHILE THE WILKINSON CURVE IS CONCAVE. FURTHERMORE, THE PEN4 SUBPREDICTOR IS ONLY VALID UP TO ABOUT 2.85 km/sec. THE MODIFIED BURCH SUBPREDICTOR IS A DECREASING CURVE AND INTERSECTS THE WILKINSON CURVE AT ABOUT 9 km/sec. ALSO SHOWN IS THE CUMULATIVE PROBABILITY DISTRIBUTION FOR SPACE DEBRIS AT 500 km ALTITUDE AND 30° INCLINATION. NOTE THAT 80% PROBABILITY OCCURS AT ROUGHLY 12 km/sec. NOTE, ALSO, THAT VELOCITIES UP TO 10 km/sec ONLY ACCOUNT FOR ROUGHLY 40% OF THE THREAT DISTRIBUTION.



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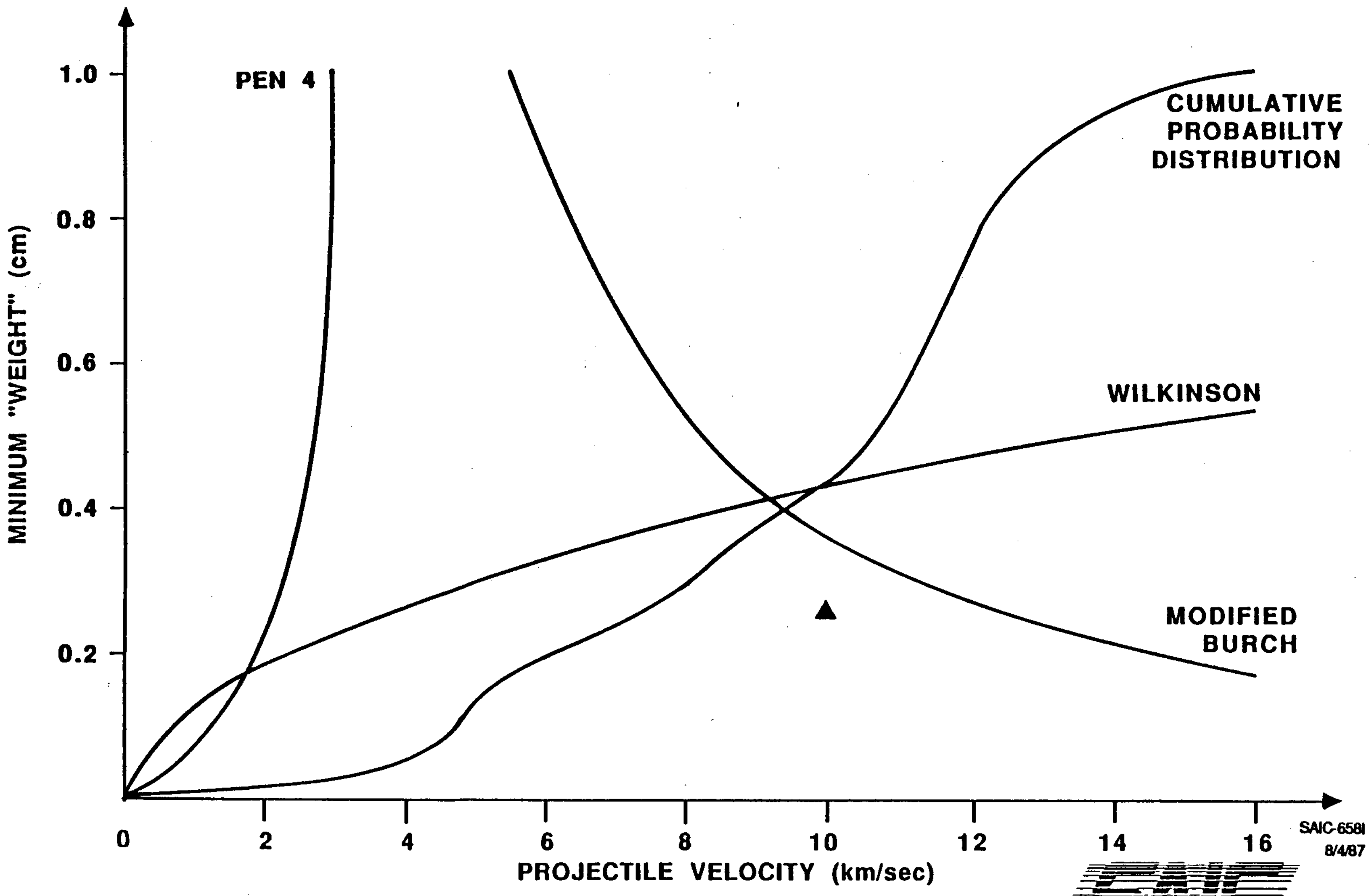
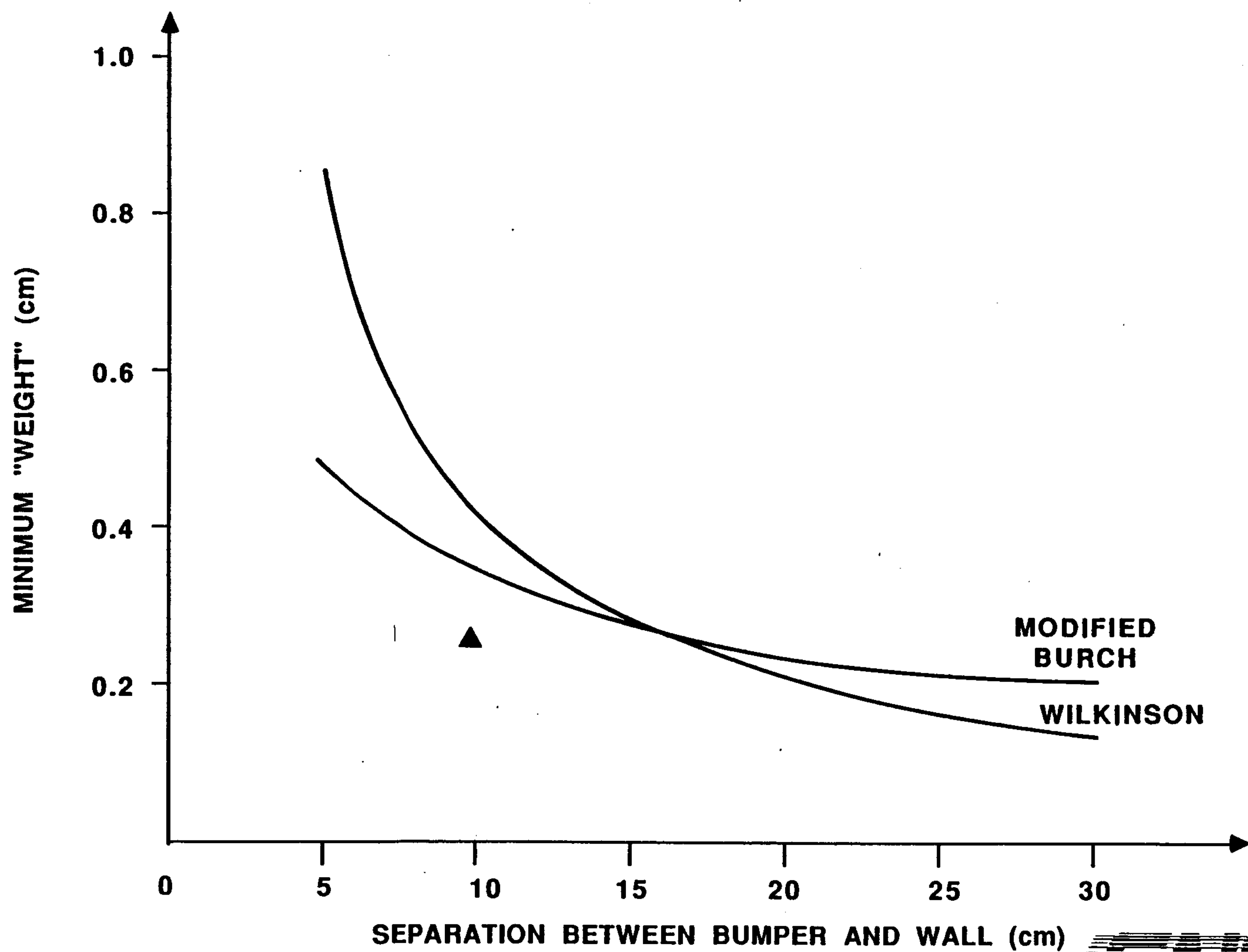
# VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS



# GP SHOWS SEPARATION SENSITIVITIES FOR MODIFIED BURCH AND WILKINSON

THE DECREASE IN OPTIMAL DESIGN FOR AN INCREASE IN BUMPER/WALL SEPARATION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS SHOWN. NOTE THAT THE WILKINSON CURVE IS MUCH MORE SENSITIVE TO INCREASES IN BUMPER/WALL SEPARATION.

# GP SHOWS SEPARATION SENSITIVITIES FOR MODIFIED BURCH AND WILKINSON

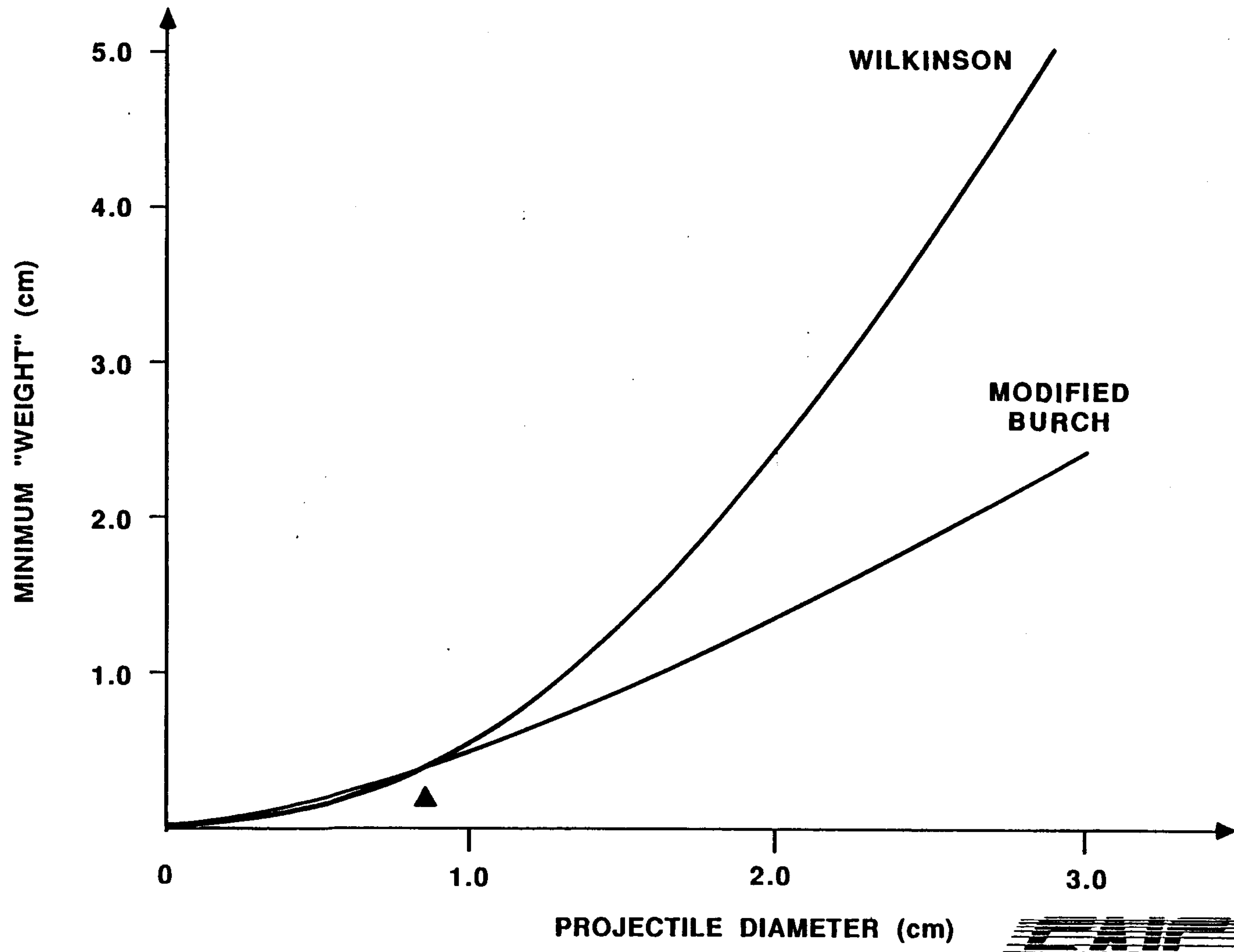



SAIC-658B
8/4/87

# SENSITIVITY OF OPTIMAL DESIGN TO THREAT

SHOWN IN THE NEXT TWO CHARTS IS THE DESIGN SENSITIVITY TO PROJECTILE DIAMETER FOR THE WILKINSON AND MODIFIED BURCH SUBPREDICTORS. NOTE THAT THE MODIFIED BURCH CURVE DOMINATES THE DESIGN UP TO ABOUT 0.52 cm PROJECTILE DIAMETER, WHERE THE WILKINSON CURVE TAKES OVER.

# SENSITIVITY OF OPTIMAL DESIGN TO THREAT




SAIC-658G
8/4/87

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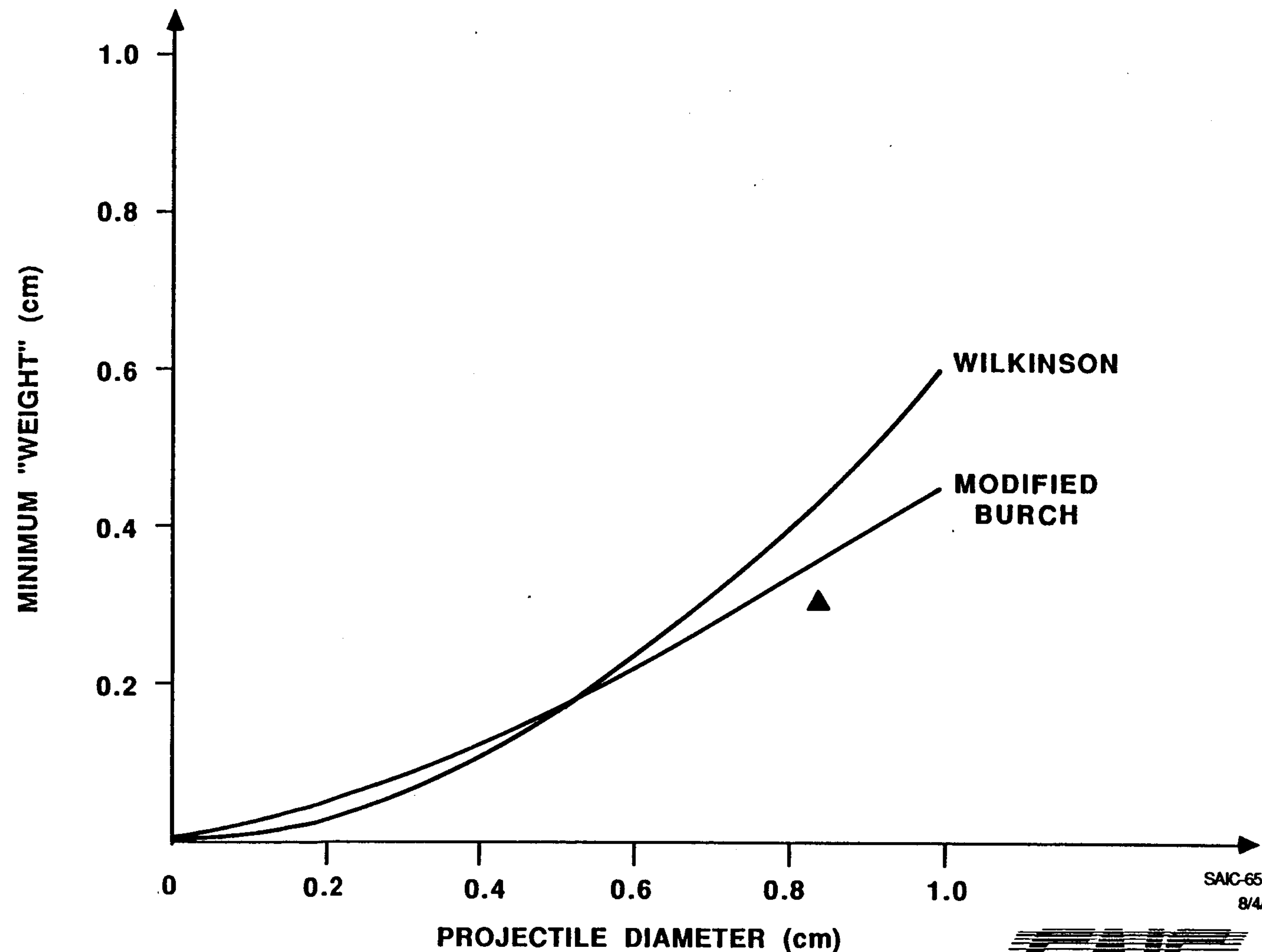
## SENSITIVITY OF OPTIMAL DESIGN TO THREAT




SAIC-658C
8/4/87

## WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH

SHOWN IS THE EFFECT OF INCREASING MISSION RISK (DECREASING PROBABILITY OF NO PENETRATION) ON OPTIMAL DESIGN FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. NOTE THAT THE WILKINSON CURVE DOMINATES EXCEPT IN THE VERY HIGH MISSION RISK REGION.

BM07-8/5

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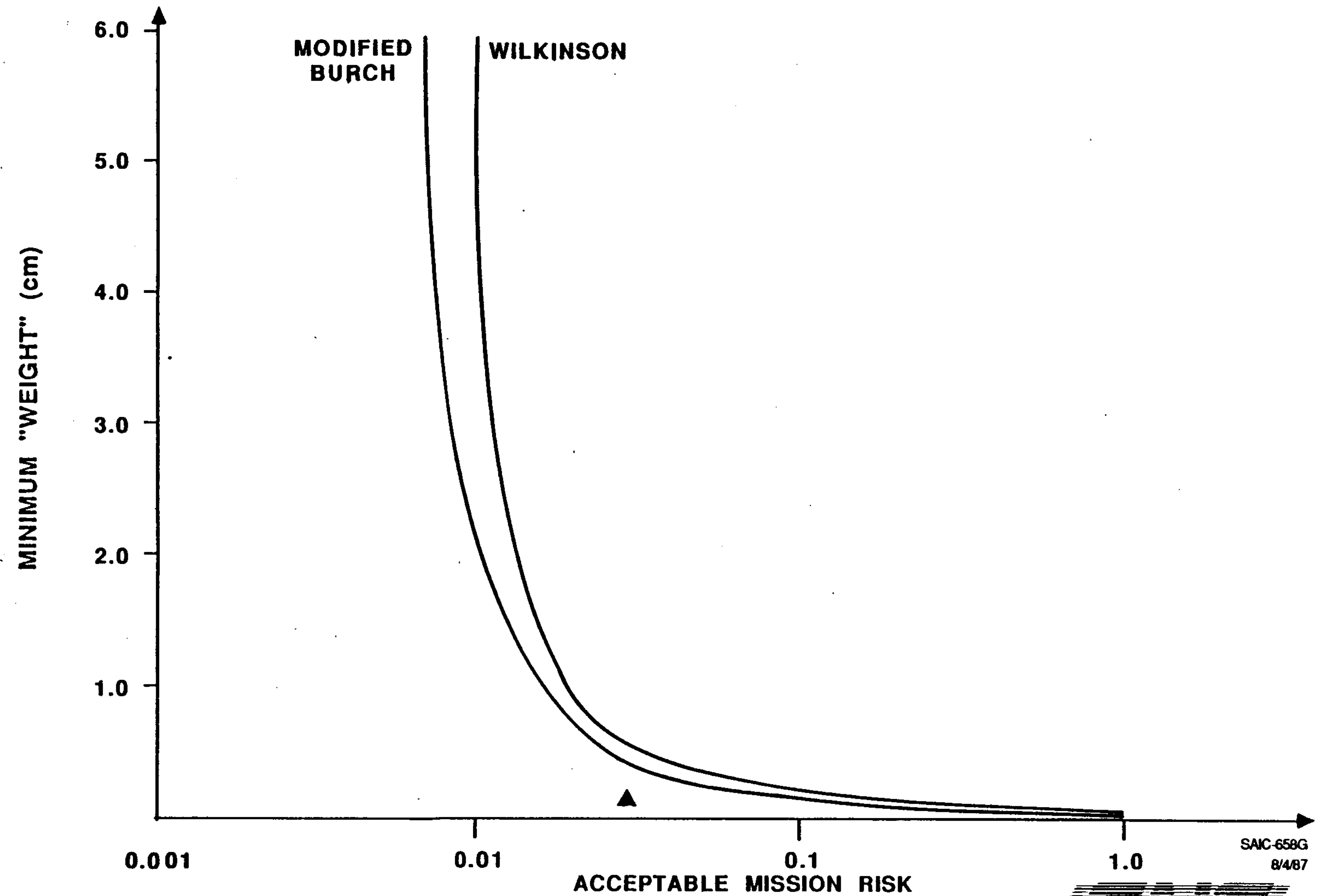
# WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH




SAIC-658G
8/4/87

# GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION IN 20-30 YEAR RANGE

THE OPTIMAL DESIGN SENSITIVITY TO MISSION DURATION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS SHOWN. EXCEPT FOR SHORT DURATION MISSIONS, THE WILKINSON CURVE DOMINATES IN AN INCREASING FASHION.



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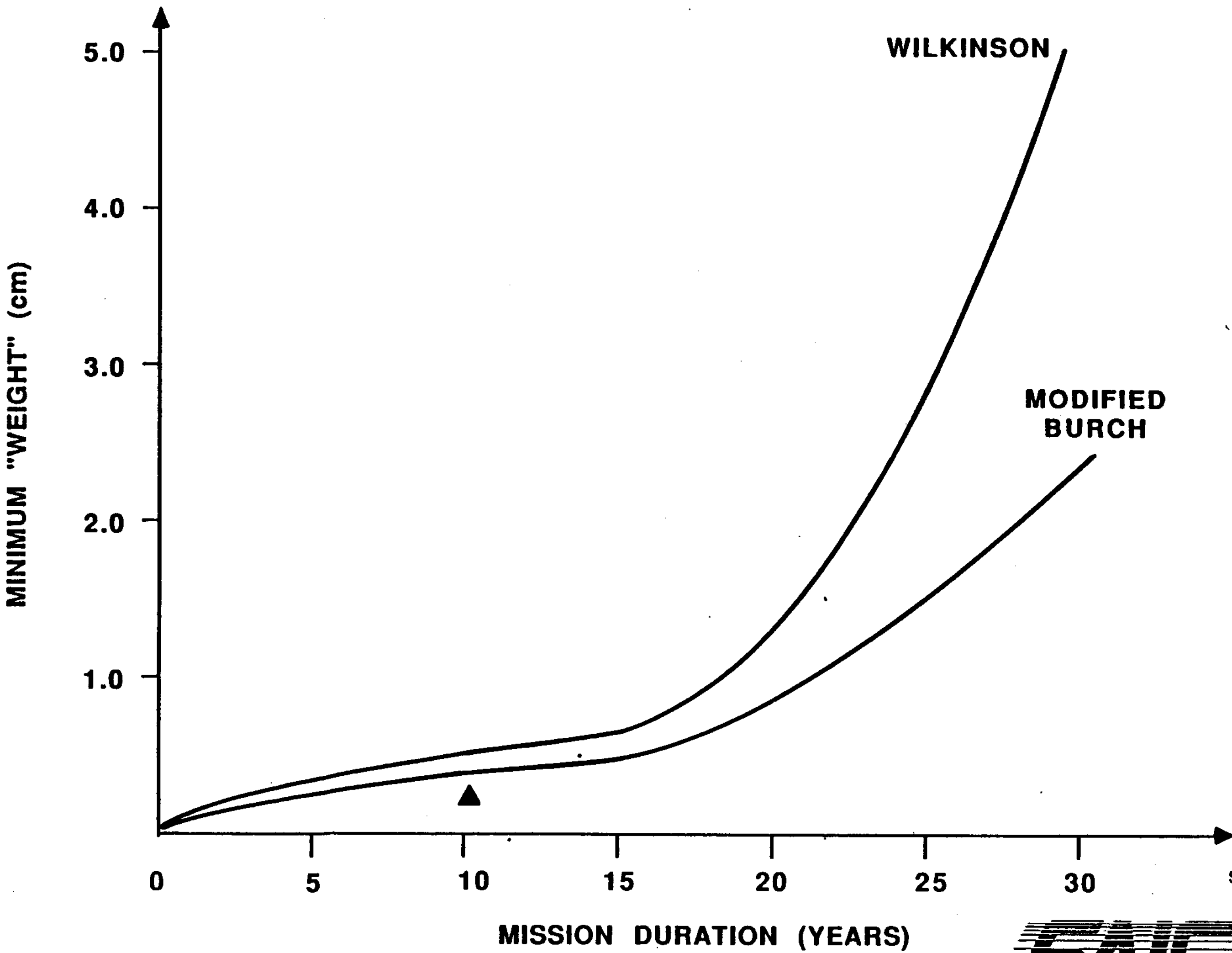
# GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION IN 20 - 30 YEAR RANGE




SAIC-658A
8/4/87

## GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS DEPICTED . THIS IS THE RATIO BETWEEN THE OPTIMAL BUMPER (OR WALL) THICKNESS AND THE TOTAL OPTIMAL THICKNESS. FOR THE MODIFIED BURCH PREDICTOR, THIS RATIO INDICATES AN OPTIMAL DISTRIBUTION OF 27%-33% BUMPER, 73%-67% WALL. FOR THE WILKINSON PREDICTOR, THE OPTIMAL DISTRIBUTION IS 50% BUMPER, 50% WALL, EXCEPT FOR LARGE DIAMETER PROJECTILES OR HIGHER VELOCITIES. IN THESE REGIONS, THE OPTIMAL DISTRIBUTION IS SKEWED TOWARD THE WALL THICKNESS.



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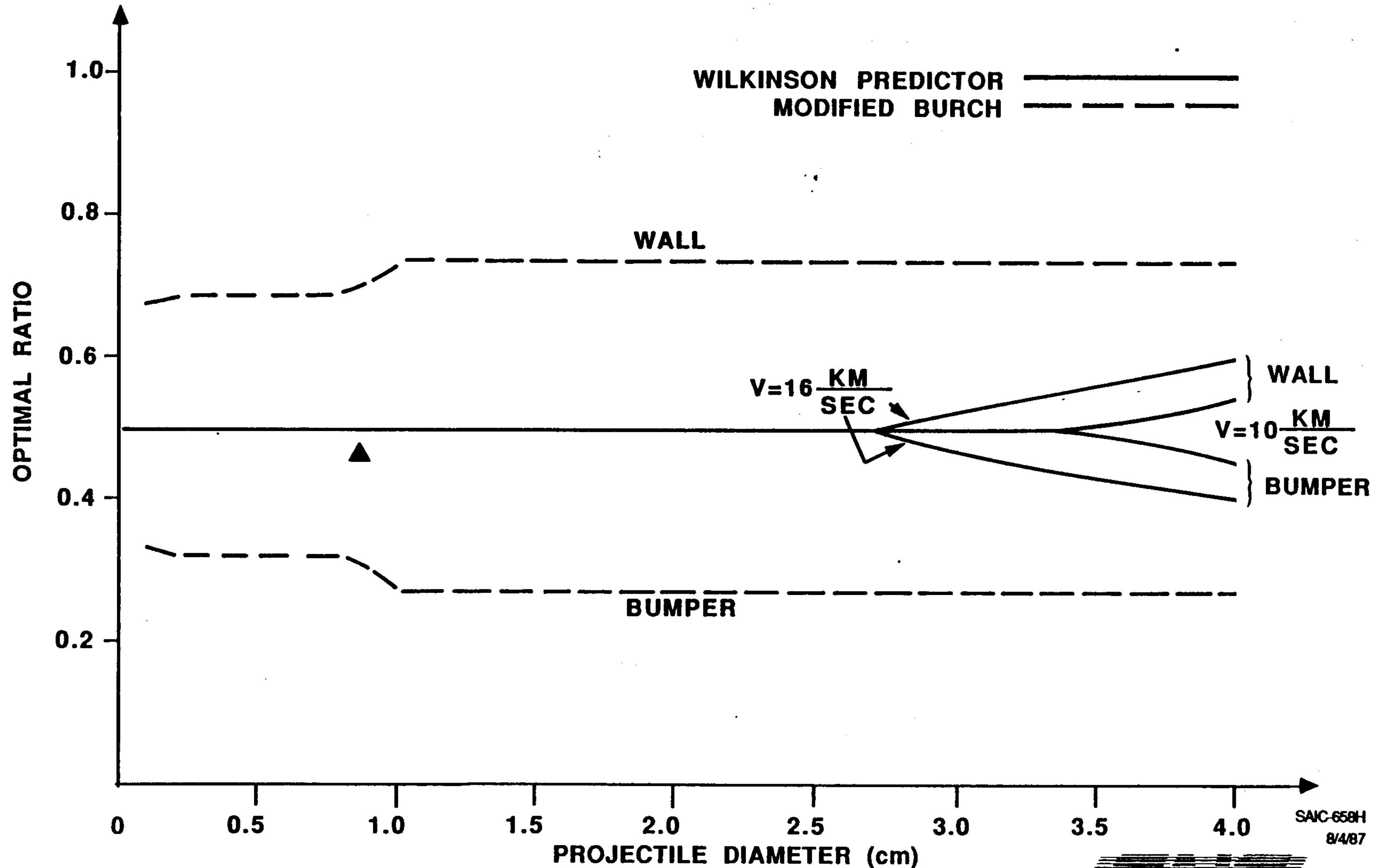
# GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS

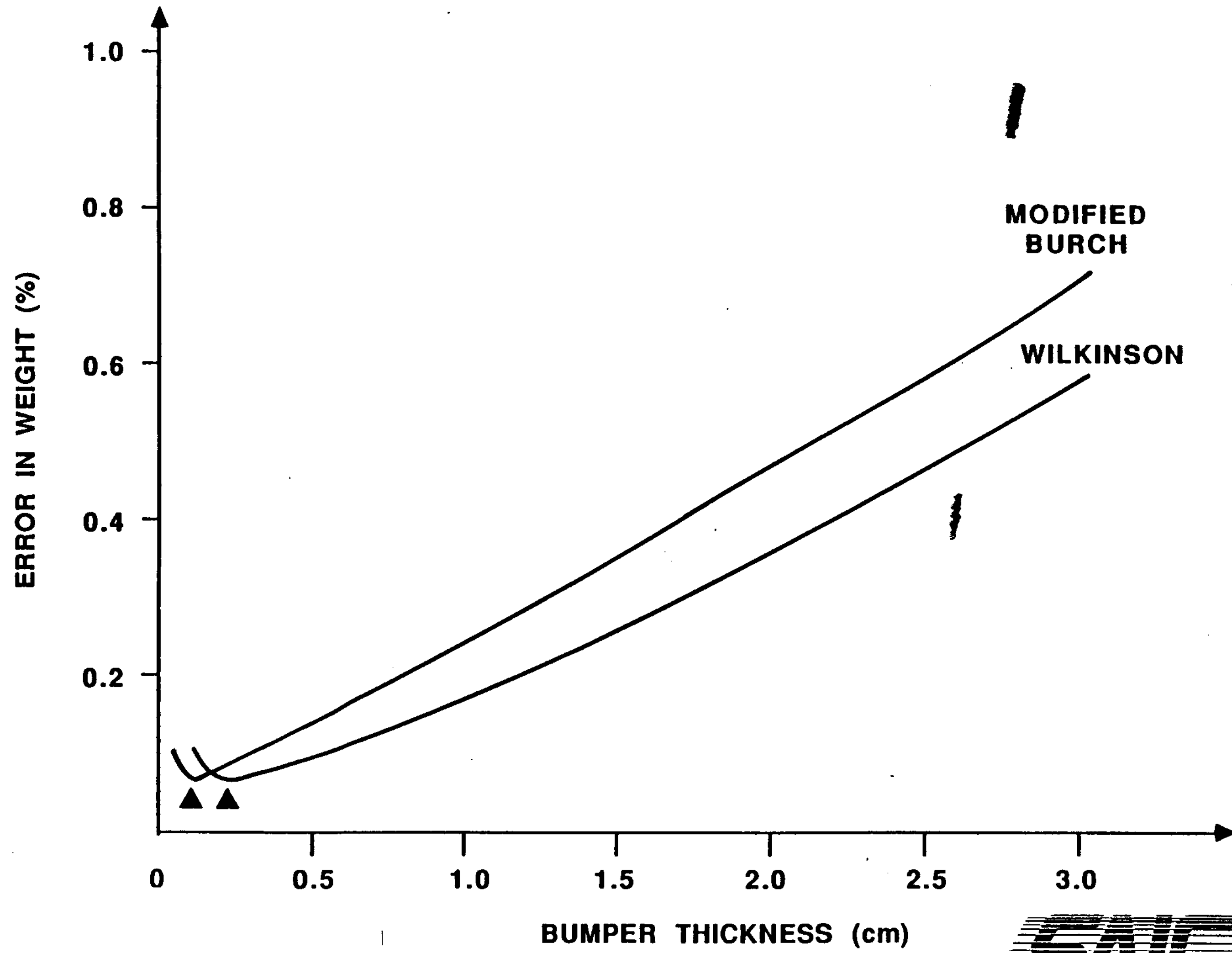



SAIC-658H
8/4/87

# LOW ERRORS ASSOCIATED WITH TWO DEGREE-OF-DIFFICULTY APPROXIMATION TO CMC WEIGHT

SHOWN IS THE EFFECT OF BUMPER THICKNESS ON THE ERROR IN DESIGN WEIGHT ASSOCIATED WITH APPROXIMATING THE FIVE DEGREE-OF-DIFFICULTY GEOMETRIC PROGRAMMING PROBLEM WITH A TWO-TERM FUNCTION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. AS IN THE NYSMITH CASE, THE ERRORS ASSOCIATED WITH THIS APPROXIMATION ARE NEGLIGIBLE.

# LOW ERRORS ASSOCIATED WITH TWO DEGREE-OF-DIFFICULTY APPROXIMATION TO CMC WEIGHT

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8/4/87

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# SECTION V

## GEOMETRIC PROGRAMMING APPLIED TO THE BOEING PREDICTOR.

BM30-8/21

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# WHAT YOU WILL SEE IN SECTION V

- BASELINE DESIGN PARAMETERS FOR THE BOEING PREDICTOR
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING PREDICTOR
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

BM5-10/13

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# BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE BOEING PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 16% BUMPER, 84% WALL.

BM03-9/9

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# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

| | | |
|---|---|---|
| $P_o$ | = 0.97 | (PROBABILITY OF NO PENETRATION) |
| $T$ | = 10 YRS | (MISSION DURATION) |
| $A_d$ | = 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = 403 $m^2$ | (METEOROID AREA) |
| Alt | = 500 km | (AVERAGE ALTITUDE) |
| $V_m$ | = 20 km/sec | (AVERAGE METEOROID VELOCITY) |
| $V_D$ | = 10 km/sec | (AVERAGE DEBRIS VELOCITY) |
| $\rho_m$ | = 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| S | = 10 cm | (BUMPER/WALL SEPARATION) |
| $\rho_1$ | = 2.8 $gm/cm^3$ | |
| $E_1$ | = $7.239 \times 10^{11}$ $gm/cm\text{-}sec^2$ | |
| $Sy_1$ | = 7344000 $lb/ft^2$ (51 Ksl) | |
| $\rho_2$ | = $\rho_1$ | |
| $Sy_2$ | = $Sy_1$ | |
| $L_2$ | = 0.401 | |
| $\theta$ | = 0 degrees | |

BM06-8/21

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# BASELINE DESIGN PARAMETERS (CONT'D)

## OPTIMAL DESIGN (BALLISTIC LIMIT)

**BUMPER**

$t_{10}$ = 0.09 cm (.04 in)

**WALL**

$t_{20}$ = 0.49 cm (.19 in)

CMC weight = 2979 Kg (6554 lb)

BM06A-8/21

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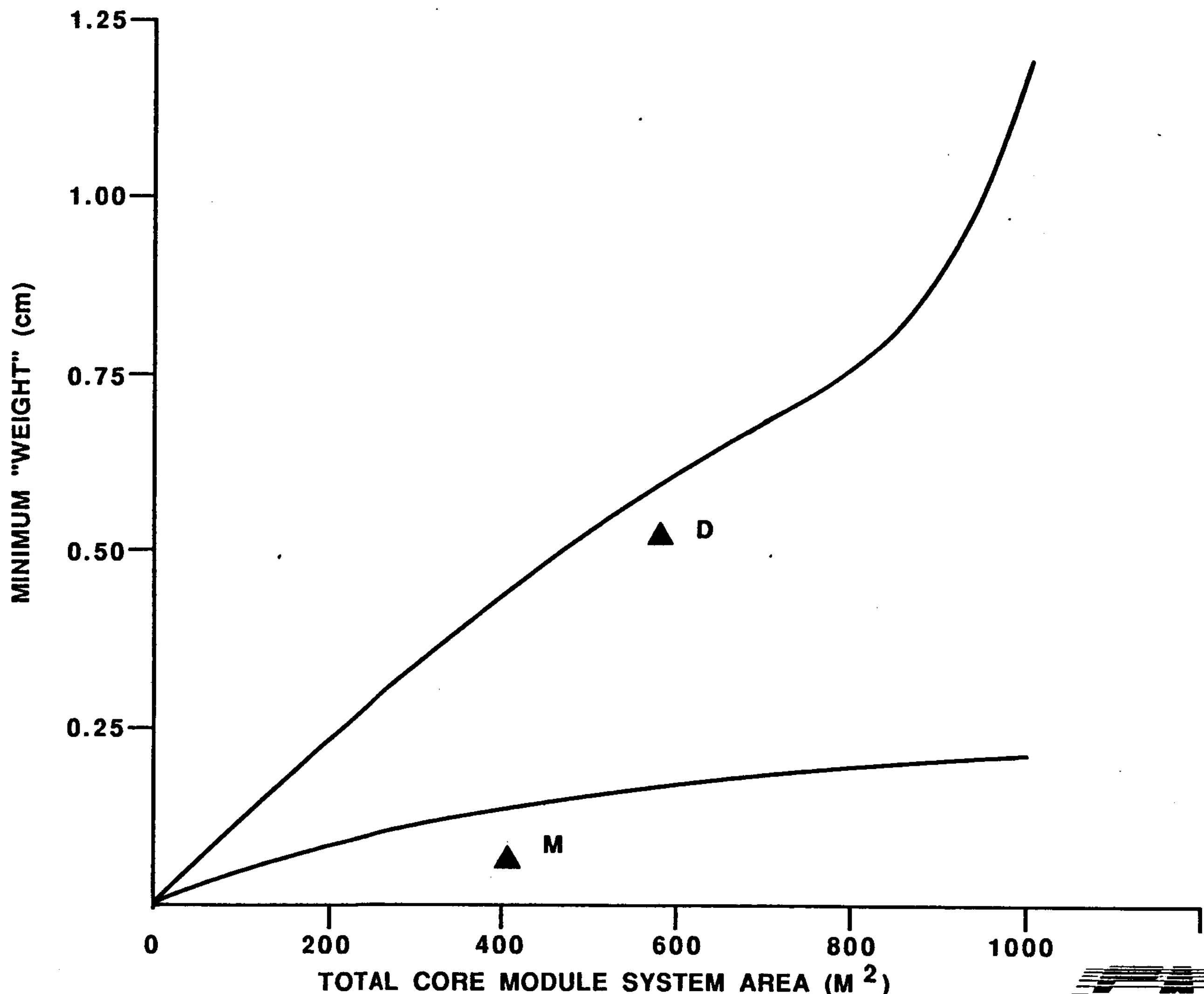
# DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT

SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN.

# DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT

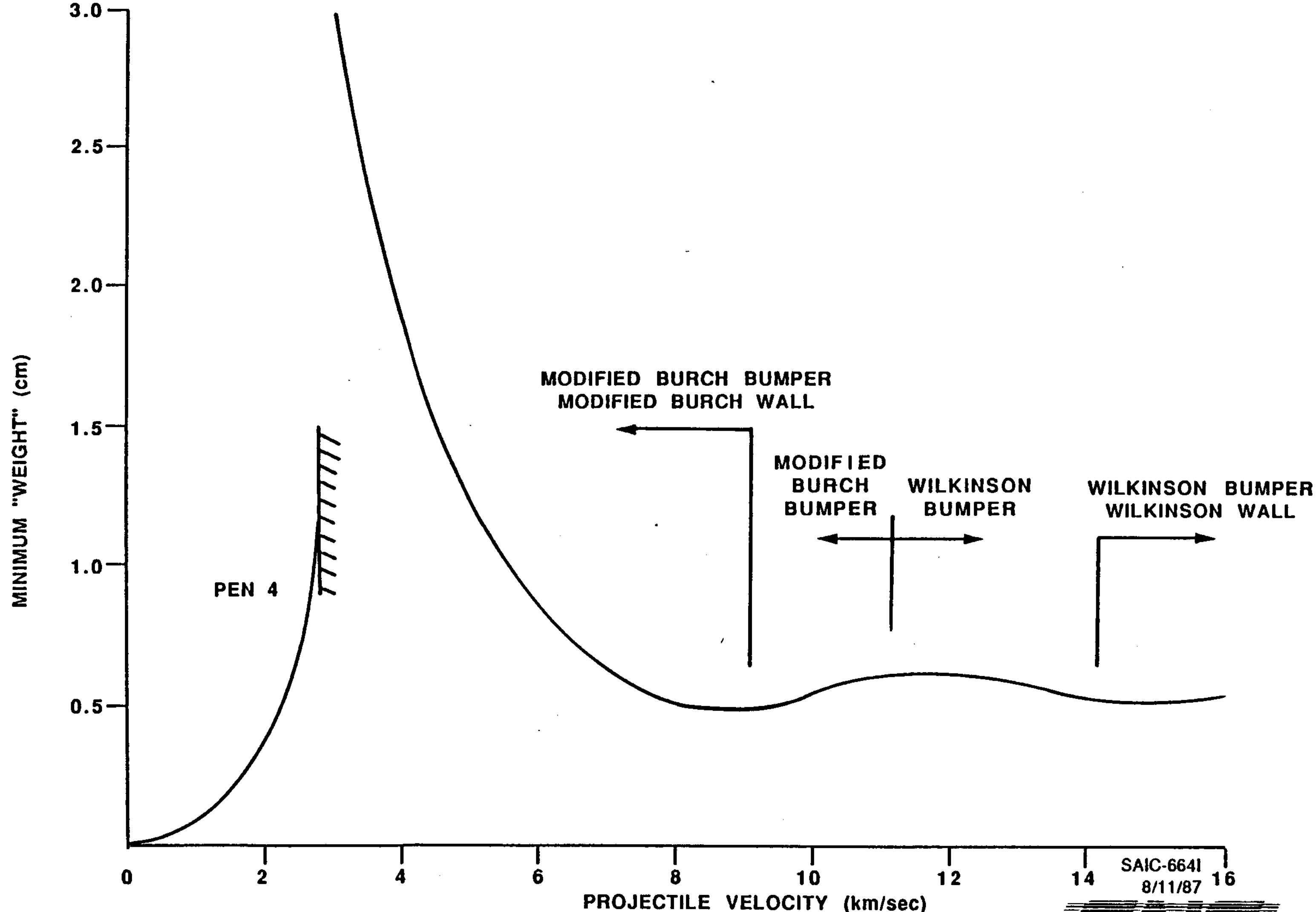



SAIC-664
8/11/87

# GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR BOEING PREDICTOR

THE EFFECT OF PROJECTILE VELOCITY ON OPTIMAL DESIGN IS SHOWN FOR THE BOEING PREDICTOR. THE PEN4 PREDICTOR IS SEGREGATED FROM THE OTHER TWO BOEING PREDICTORS AS IT IS ONLY VALID UP TO 2.8 km/sec. ON COMPARISON WITH THE CORRESPONDING TRADE FOR THE THREE BOEING SUBPREDICTORS, IT IS EASY TO SEE THAT THE MODIFIED BURCH OPTIMAL DESIGN DOMINATES BETWEEN 2.8 km/sec AND 9 km/sec, AND THE WILKINSON OPTIMAL DESIGN DOMINATES FROM 14 TO 16 km/sec. BETWEEN 9 AND 11 km/sec, THE MODIFIED BURCH OPTIMAL BUMPER DESIGN IS CHOSEN ALONG WITH THE WILKINSON WALL DESIGN INDUCED BY THIS BUMPER. FROM 11 TO 14 km/sec, THE ROLES OF THE TWO PREDICTORS ARE REVERSED.

# GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR BOEING PREDICTOR




SAIC-6641
8/11/87

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## GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR

SHOWN IS THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR THE BOEING PREDICTOR. NOTE THE LARGE INCENTIVE (A REDUCTION IN DESIGN OF 40%) FOR INCREASING THE BUMPER/WALL SEPARATION BY 50% TO 15CM.

BM09-8/11

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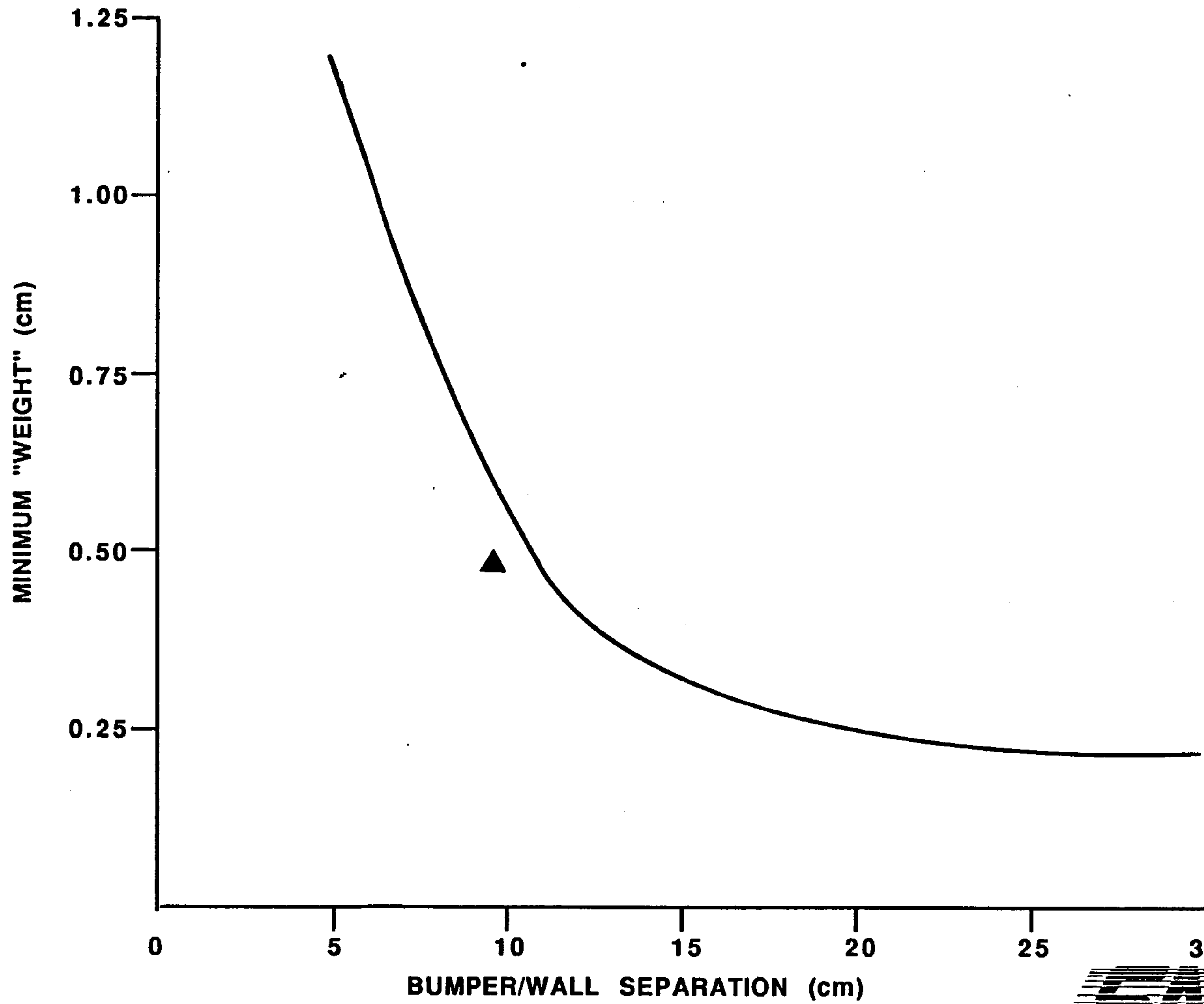
## GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR




SAIC-664F
8/11/87

## LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR

SHOWN IS THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER FOR THE BOEING PREDICTOR. NOTE THE LARGE SENSITIVITY FOR PROJECTILE DIAMETERS GREATER THAN ABOUT 1CM, WHERE THE SLOPES INCREASE TO 2-3.



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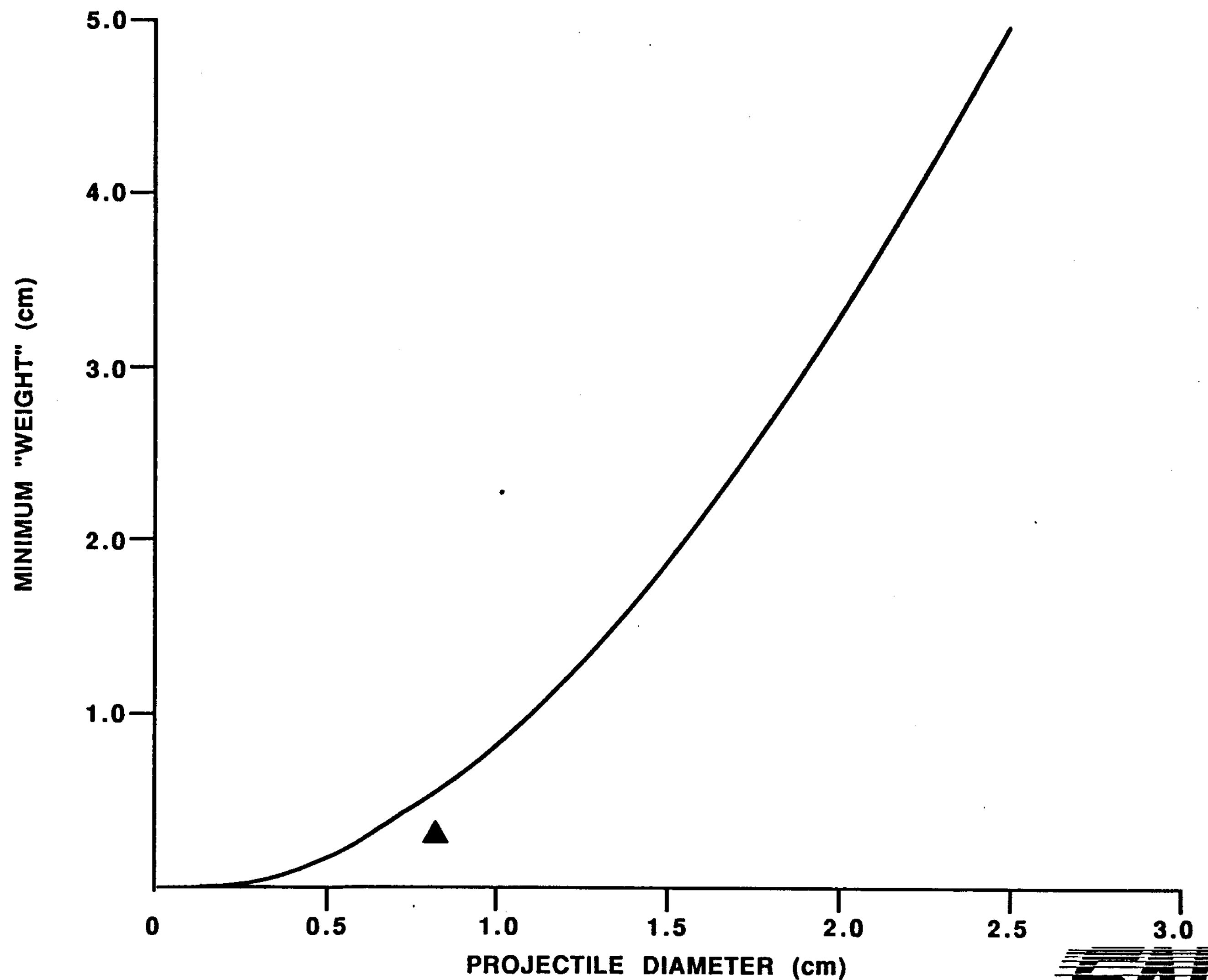
# LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR




SAIC-664A
8/11/87

# LARGE DESIGN PENALTY INDUCED BY INCREASE IN PROBABILITY OF NO PENETRATION: BOEING PREDICTOR

THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL DESIGN IS SHOWN FOR THE BOEING PREDICTOR. NOTE THE DRASTIC INCREASE IN OPTIMAL DESIGN FOR PROBABILITY OF NO PENETRATION ABOVE 0.97.

BM11-8/11

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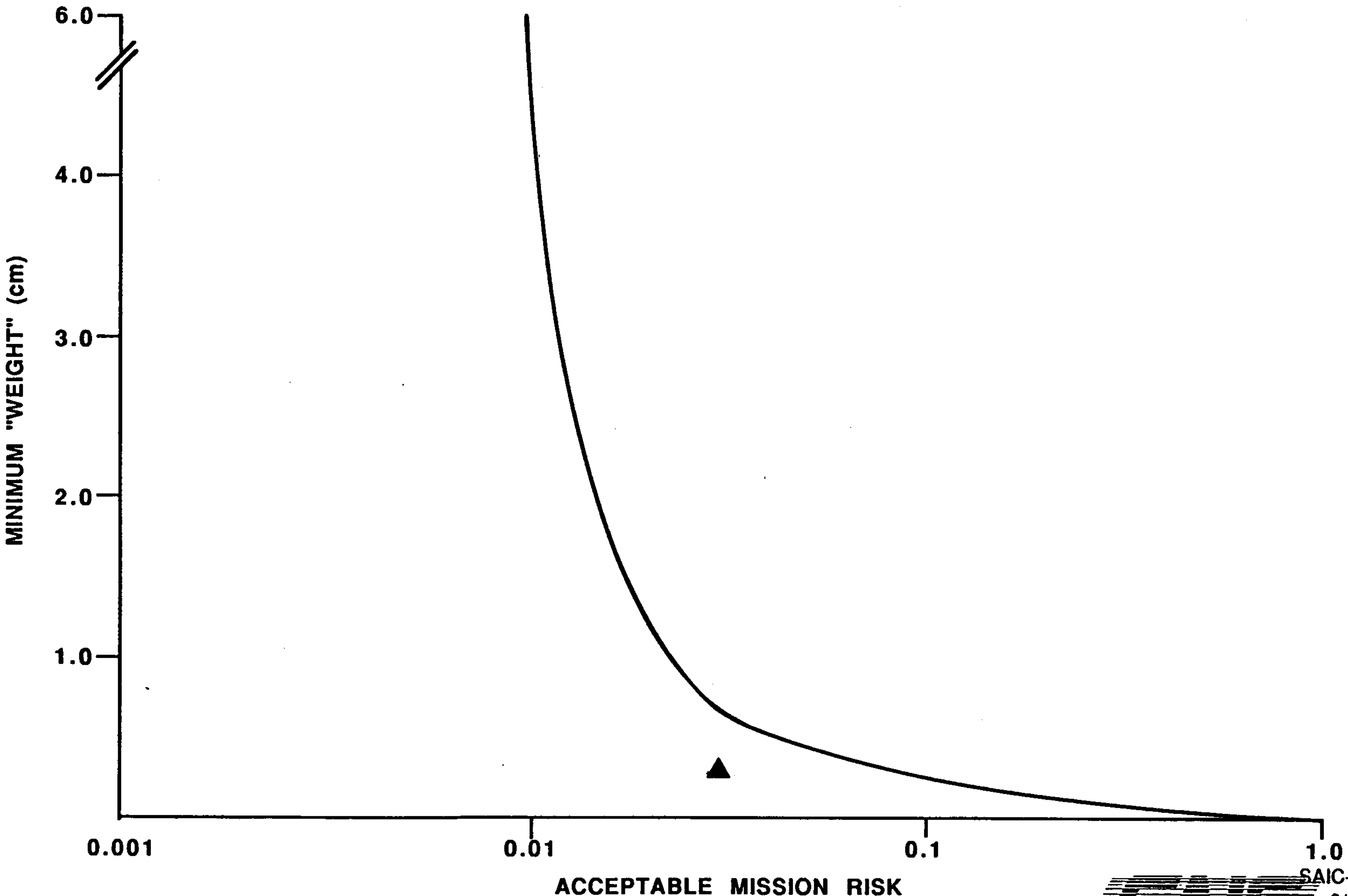
# LARGE DESIGN PENALTY INDUCED BY INCREASE IN PROBABILITY OF NO PENETRATION: BOEING PREDICTOR




SAIC-664H
8/11/87

## SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR

THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR IS SHOWN. THE INFLECTION AT 15 YEARS, AND THE SHARP INCREASE IN SLOPE AT ABOUT 22 YEARS RAISE SERIOUS DESIGN QUESTIONS FOR MISSION PLANNERS ABOUT LONG-DURATION MISSIONS.

BM12-8/11

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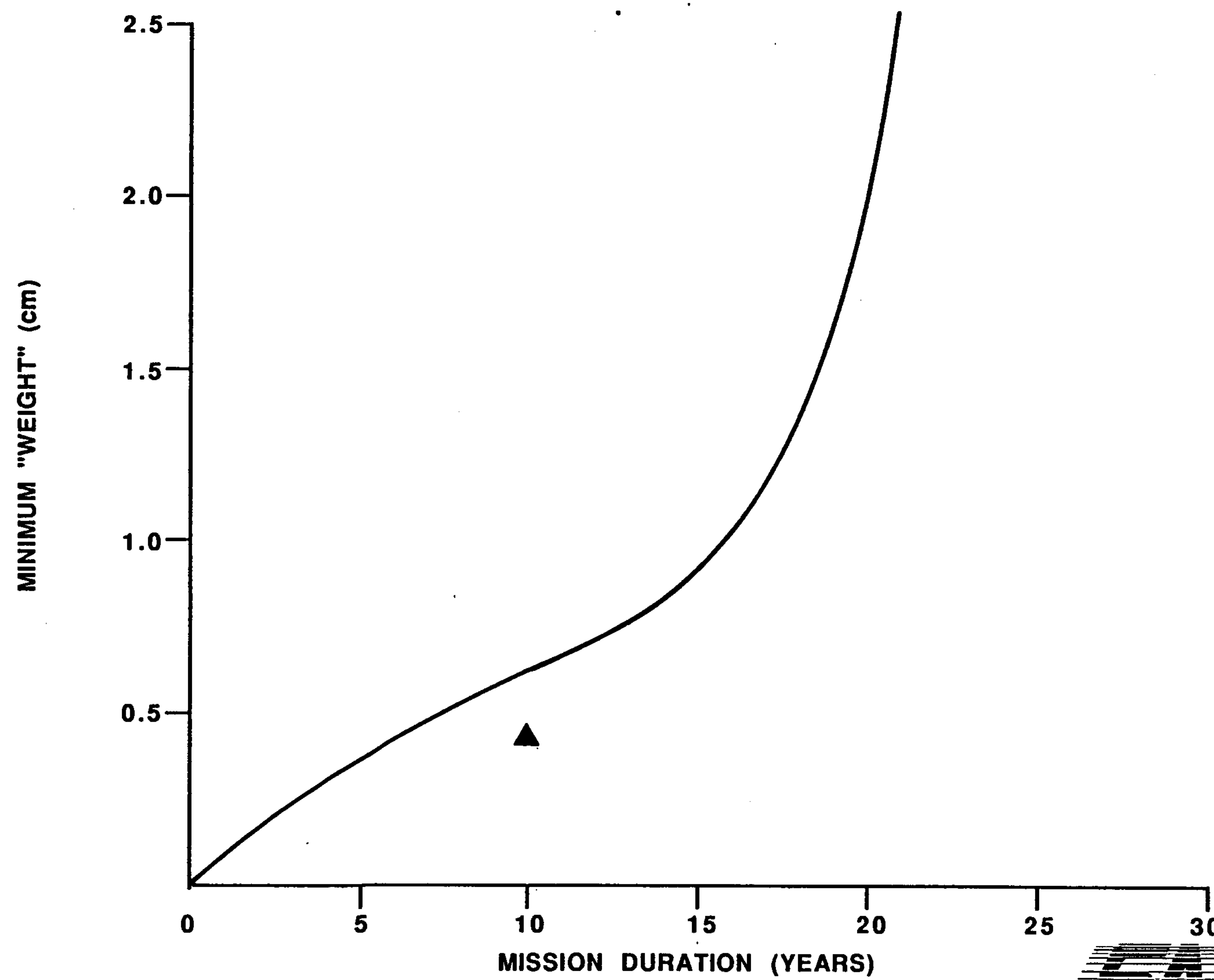
# SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR

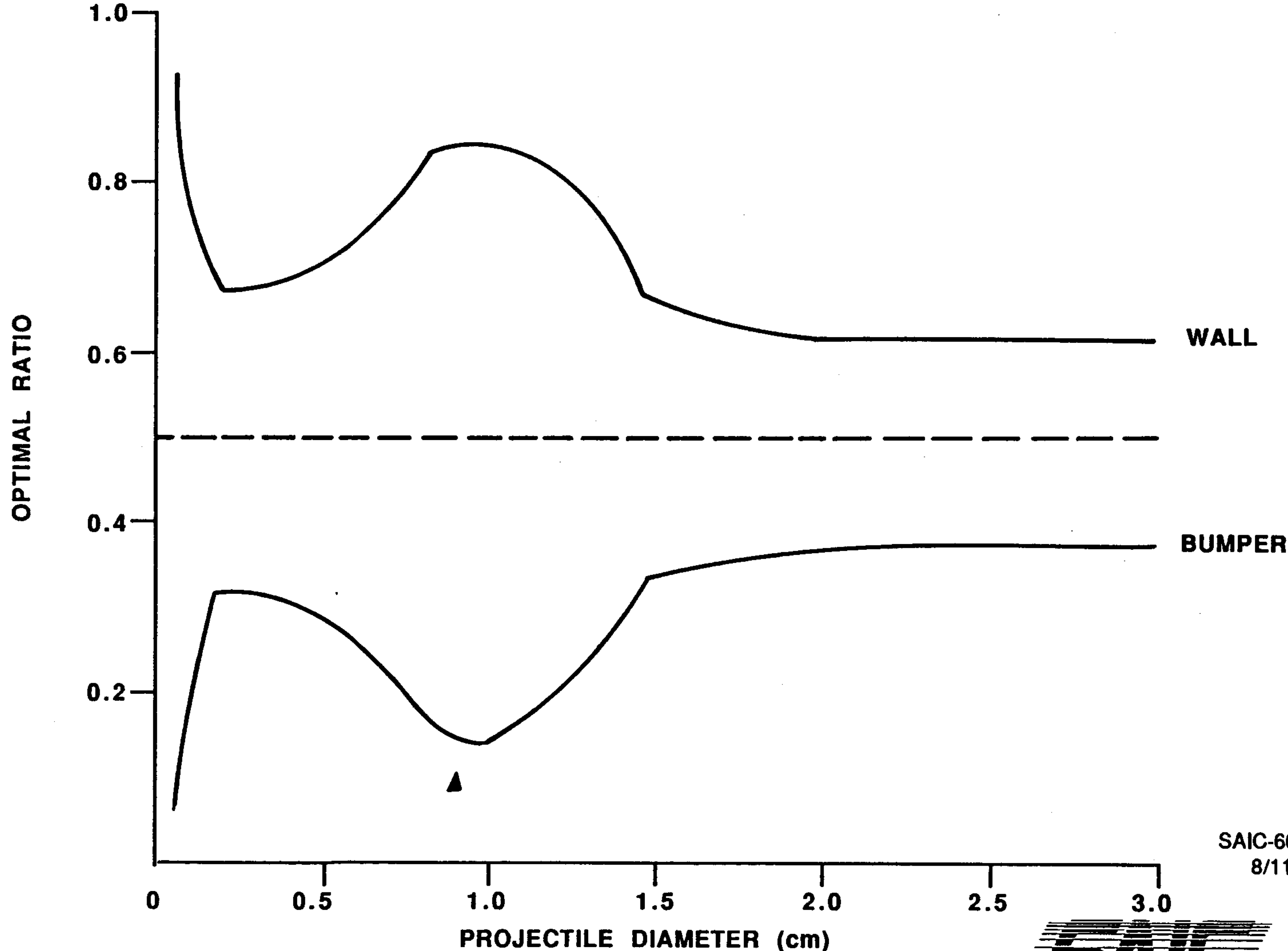



SAIC-664D
8/11/87

# GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER IS DEPICTED FOR THE BOEING PREDICTOR. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NON-LINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS.

# GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR




SAIC-664C
8/11/87

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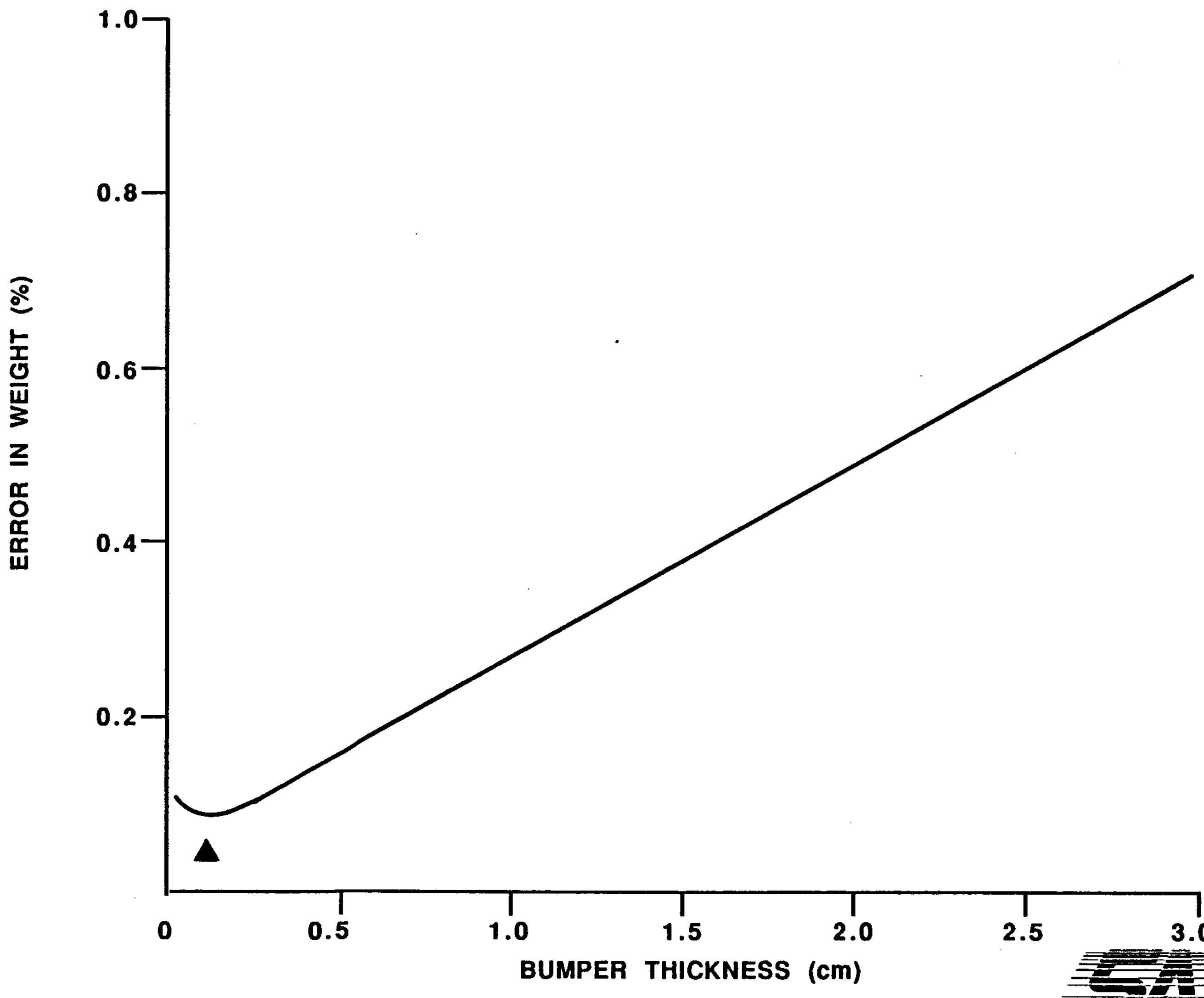
## SMALL ERRORS ASSOCIATED WITH REDUCTION OF DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR

THE ERROR IN CORE MODULE CONFIGURATION WEIGHT AS A FUNCTION OF BUMPER THICKNESS IS SHOWN FOR THE BOEING PREDICTOR. THIS REPRESENTS THE ERROR INDUCED BY REDUCING THE GP OPTIMIZATION PROBLEM FROM 5 DEGREES-OF-DIFFICULTY TO TWO. NOTE THAT THE ERROR IS NEGLIGIBLE IN A LARGE NEIGHBORHOOD OF THE BASELINE DESIGN.

## SMALL ERRORS ASSOCIATED WITH REDUCTION OF DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR




SAIC-664G
8/11/87

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# SECTION VI

## GEOMETRIC PROGRAMMING APPLIED TO THE VELOCITY-INTEGRATED BOEING PREDICTOR.

BM31-8/21

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# WHAT YOU WILL SEE IN SECTION VI

- ALGORITHM AND BASELINE DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- THE SENSITIVITY OF OPTIMAL DESIGN TO ORBITAL INCLINATION
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER
- COST EXCURSIONS
- SUMMARY OF PREDICTOR RESULTS



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## BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE VELOCITY-INTEGRATED BOEING PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 21% BUMPER, 79% WALL.

BM04-9/9

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# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

| | | |
|---|---|---|
| $P_o$ | = 0.97 | (PROBABILITY OF NO PENETRATION) |
| T | = 10 yrs | (MISSION DURATION) |
| $A_d$ | = 574 $m^2$ | (DEBRIS AREA) |
| $A_m$ | = 403 $m^2$ | (METEOROID AREA) |
| Alt | = 500 km | (AVERAGE ALTITUDE) |
| $\rho_m$ | = 0.5 $gm/cm^3$ | (METEOROID DENSITY) |
| $\rho_D$ | = 2.81 $gm/cm^3$ | (DEBRIS DENSITY) |
| S | = 10 cm | (BUMPER/WALL SEPARATION) |
| $\rho_1$ | = 2.81 $gm/cm^3$ | |
| $E_1$ | = $7.239 \times 10^{11}$ $gm/cm\text{-}sec^2$ | |
| $Sy_1$ | = 7344000 $lb/ft^2$ (51 Ksi) | |
| $\rho_2$ | = $\rho_1$ | |
| $Sy_2$ | = $Sy_1$ | |
| $L_2$ | = 0.401 | |
| $\theta$ | = 0 degrees | |

## OPTIMAL DESIGN (BALLISTIC LIMIT)

**BUMPER**

$t_{10}$ = 0.16cm (0.06 In)

**WALL**

$t_{20}$ = 0.59 cm (0.23 In)

CMC weight = 3837 Kg (8441 lb)

BM07-8/21

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# VELOCITY PROBABILITY DISTRIBUTIONS

**SHOWN IS THE 500km VELOCITY PROBABILITY DISTRIBUTION FOR 30 AND 60 DEGREE INCLINATIONS FROM DON KESSLER'S JSC-20001. NOTE THAT THE 60 DEGREE INCLINATION DISTRIBUTION IS HIGHLY SKEWED TOWARD THE HIGHER VELOCITIES.**

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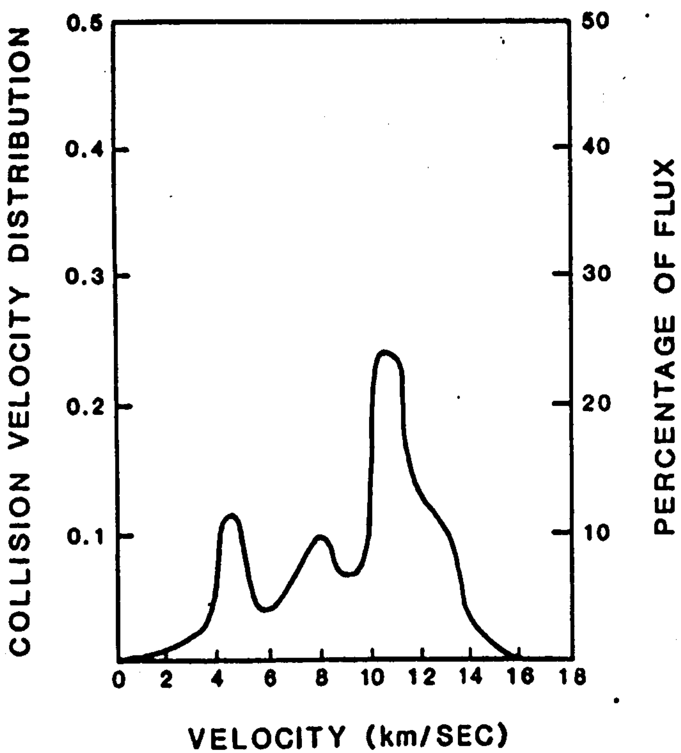
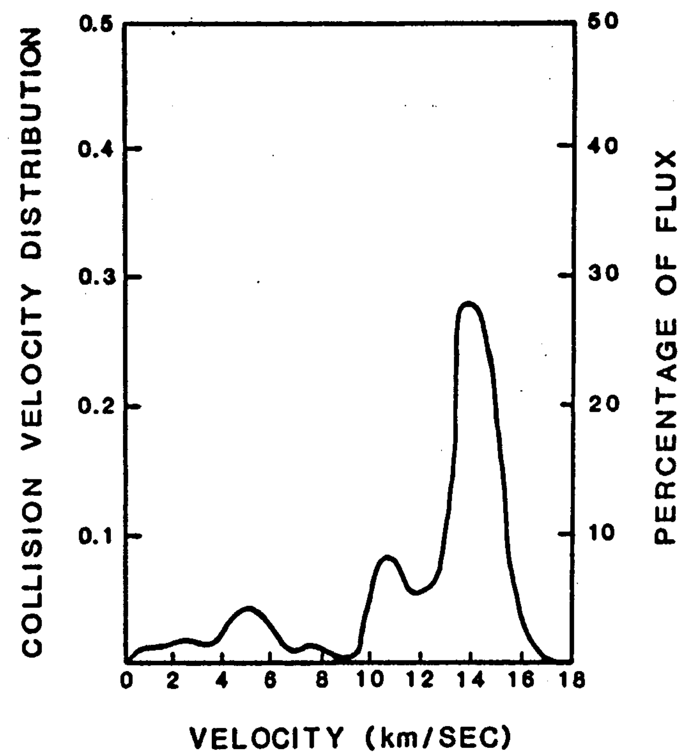
# VELOCITY PROBABILITY DISTRIBUTIONS

ALTITUDE: 500 km
INCLINATION: 30°




ALTITUDE: 500 km
INCLINATION: 60°

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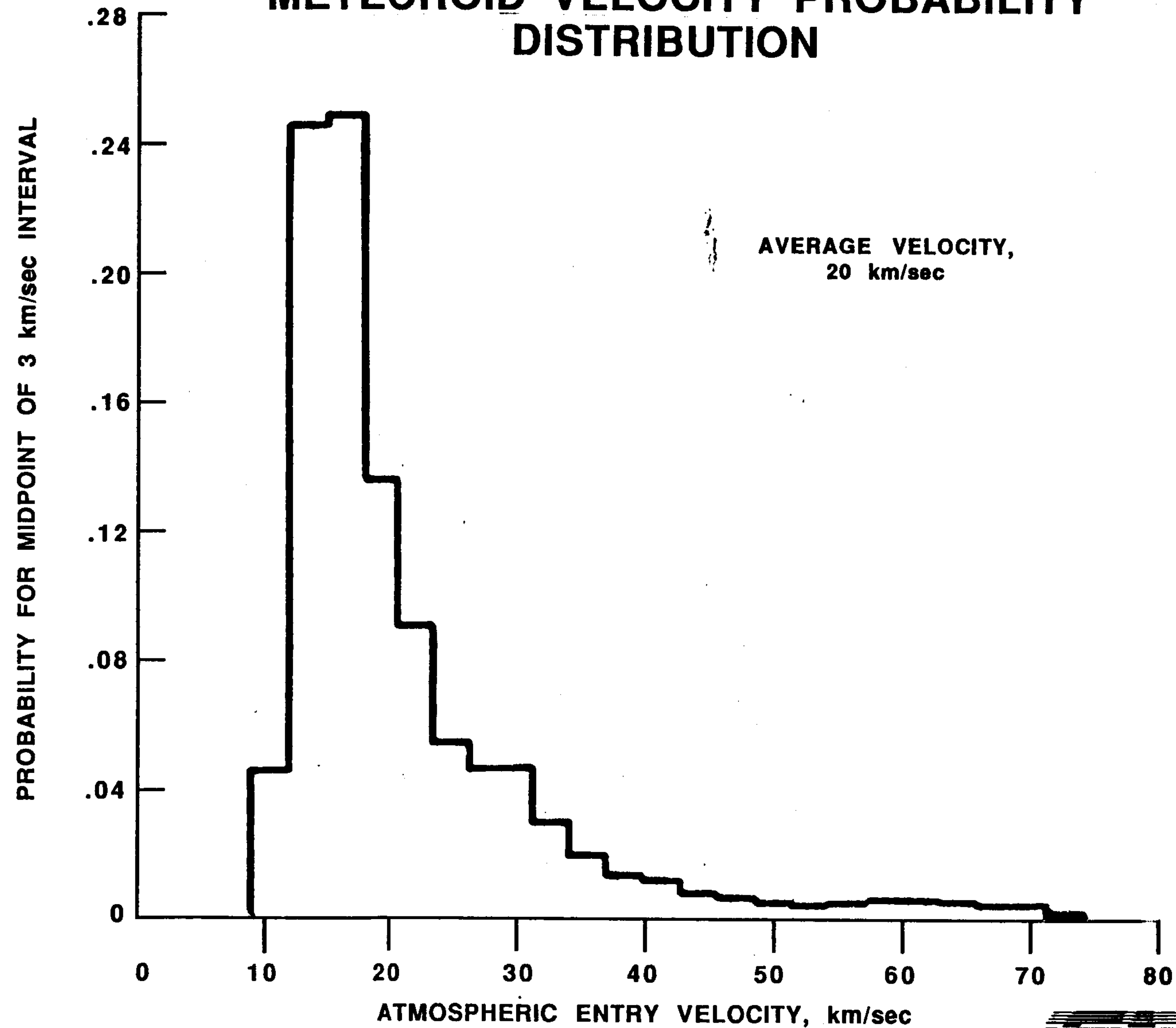
# METEOROID VELOCITY PROBABILITY DISTRIBUTION

AN APPROXIMATE VELOCITY PROBABILITY DISTRIBUTION FOR THE METEOROID SCENARIO IS SHOWN. AVERAGE VELOCITY IS ROUGHLY 20 KM/SEC. THIS DISTRIBUTION IS REFERENCED IN BURT COUR-PALAIS "METEOROID ENVIRONMENT MODEL - 1969 (NEAR-EARTH TO LUNAR SURFACE," NASA SP-8013, MARCH 1969.

# METEOROID VELOCITY PROBABILITY DISTRIBUTION



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## ALGORITHM FOR VELOCITY-INTEGRATED BOEING PREDICTOR

(1) DETERMINE VELOCITY INTERVALS.

(2) FOR MIDPOINT OF INTERVAL, DETERMINE OPTIMAL DESIGN FOR BOEING PREDICTOR.

(3) MULTIPLY OPTIMAL DESIGN BY APPROPRIATE VELOCITY PROBABILITY AT INTERVAL MIDPOINT; THEN MULTIPLY BY INTERVAL LENGTH.

(4) SUM THE PRODUCT IN (3) OVER THE ENTIRE RANGE OF VELOCITIES TO DETERMINE THE OVERALL OPTIMAL DESIGN.

BM18-9/9

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# DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT

SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR FOR THE BASELINE 30 DEGREE INCLINATION AND A 60 DEGREE INCLINATION. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN. FURTHERMORE, NOTE THE 20% DECREASE IN DESIGN INDUCED BY A 60° INCLINATION.

BM01-8/11

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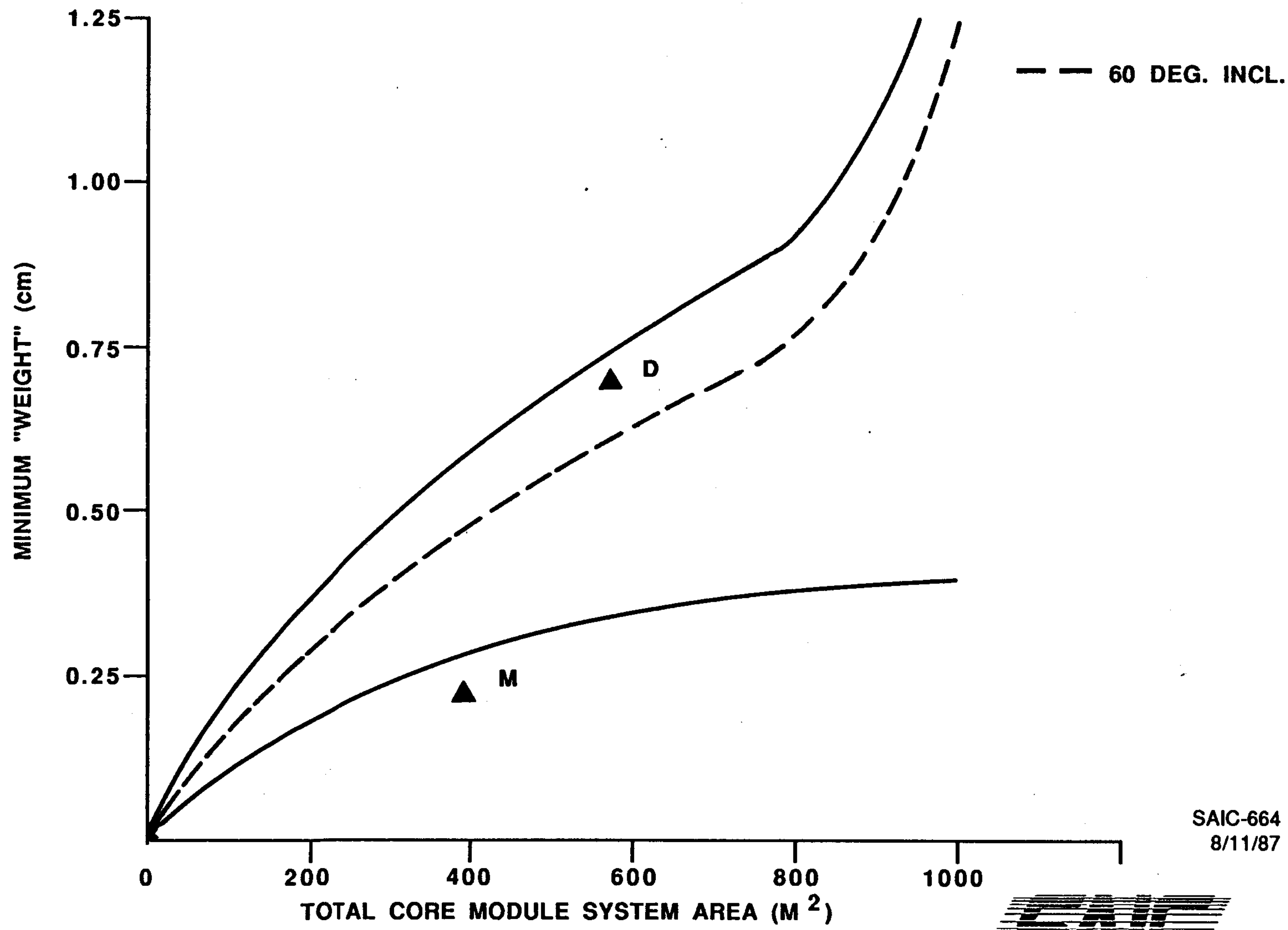
## DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT



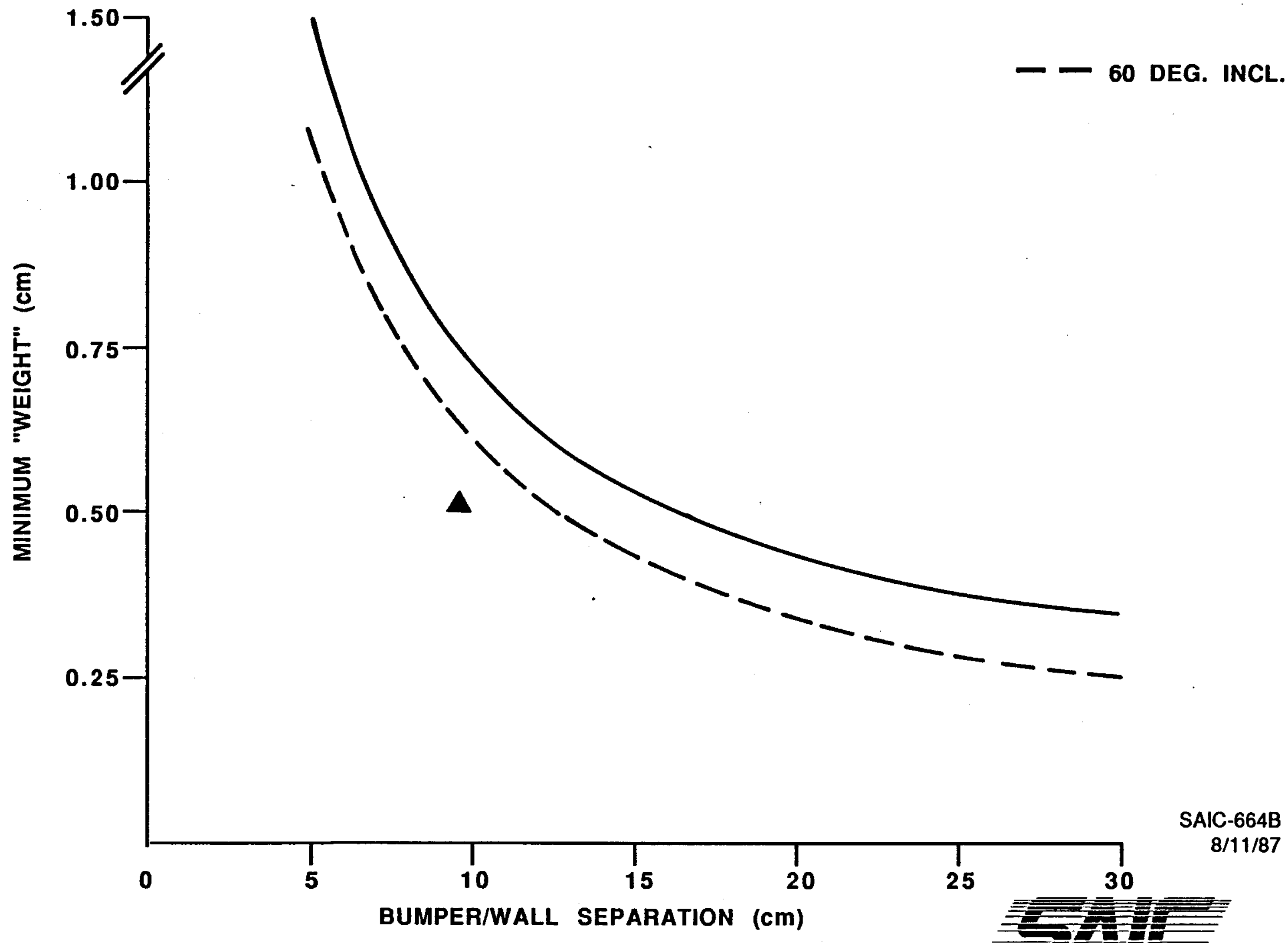

SAIC-664
8/11/87

SAIC

# GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR

THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE THE LARGE INCENTIVE (A REDUCTION IN DESIGN OF 40%) FOR INCREASING THE BUMPER/WALL SEPARATION BY 50% TO 15 CM.

## GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR




SAIC-664B
8/11/87

SAIC

# LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR

THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE THE LARGE SENSITIVITY FOR PROJECTILE DIAMETERS GREATER THAN ABOUT 1 CM, WHERE THE SLOPES INCREASE TO 2-3.

BM03-8/11

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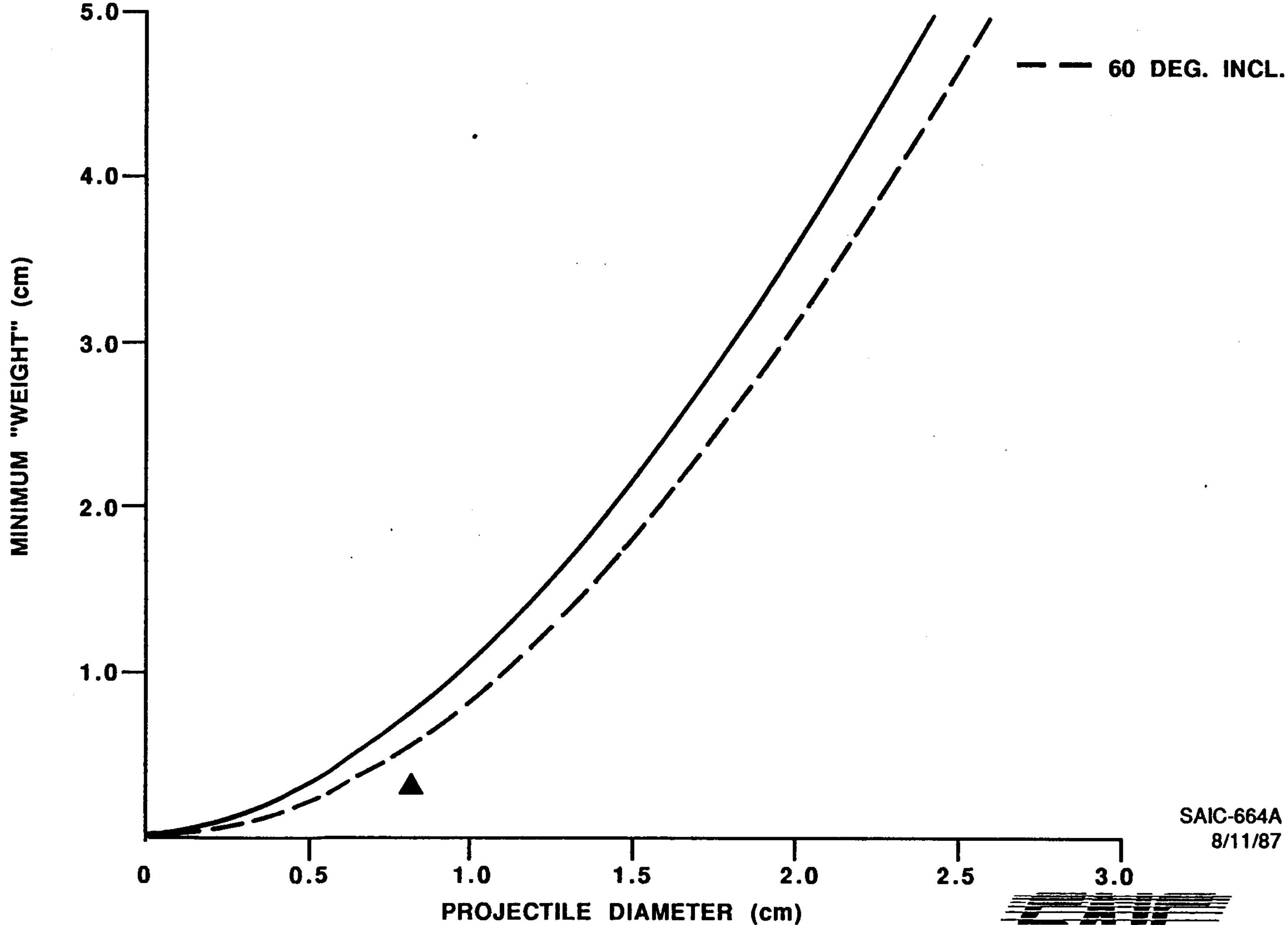
# LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR

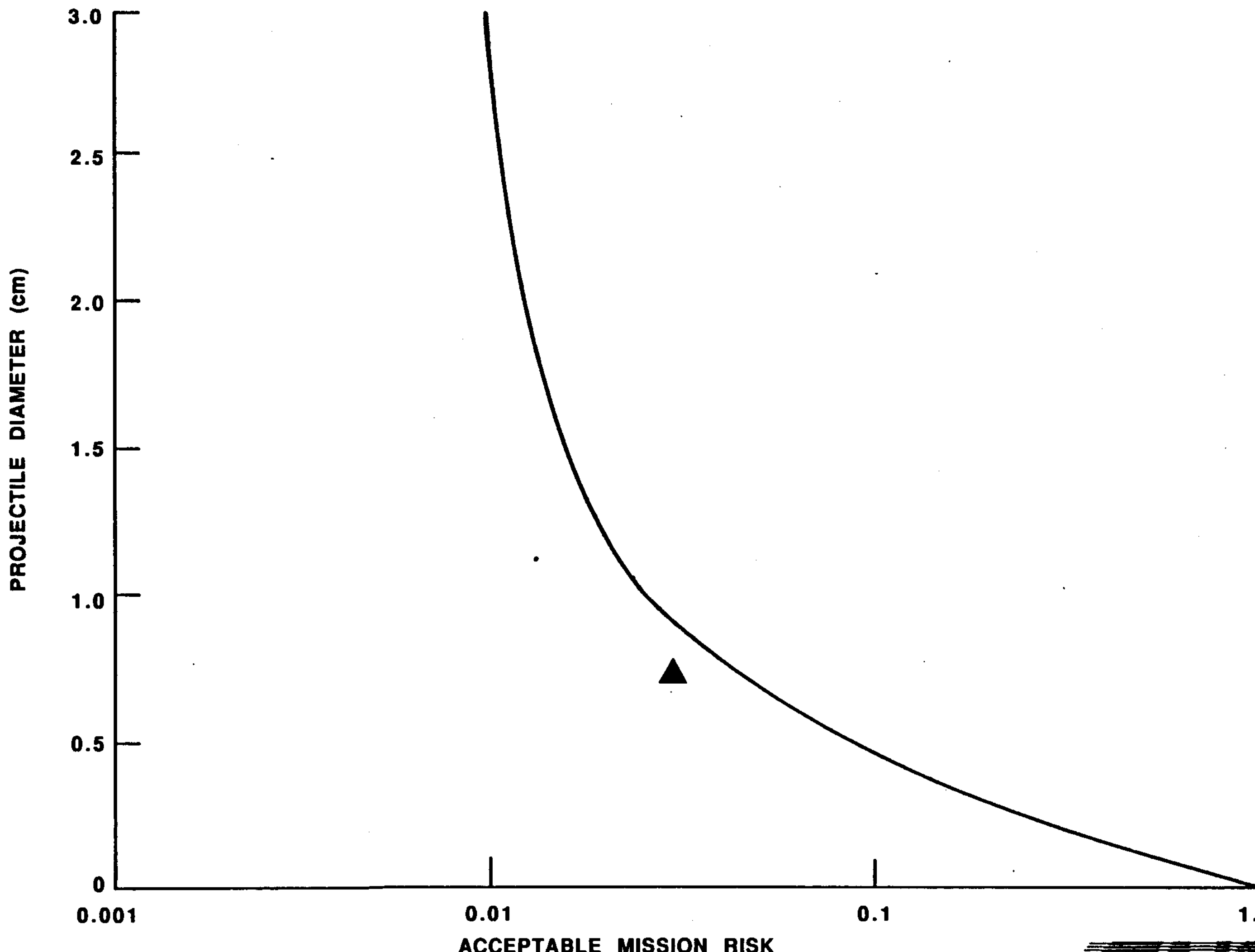



SAIC-664A
8/11/87

# EFFECT OF MISSION RISK ON PROJECTILE DIAMETER

THE EFFECT OF MISSION RISK ON PROJECTILE DIAMETER IS SHOWN FOR THE DEBRIS SCENARIO. NOTE THAT AN INCREASE IN PROBABILITY OF NO PENETRATION FROM THE BASELINE INDUCES A LARGE INCREASE IN REQUIRED DESIGN.

# EFFECT OF MISSION RISK ON PROJECTILE DIAMETER

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## SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN PROBABILITY OF NO PENETRATION: BOEING PREDICTOR

**SHOWN IS THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCLINATIONS. NOTE THE DRASTIC INCREASE IN OPTIMAL DESIGN FOR PROBABILITY OF NO PENETRATION ABOVE 0.97.**

BM04-8/11

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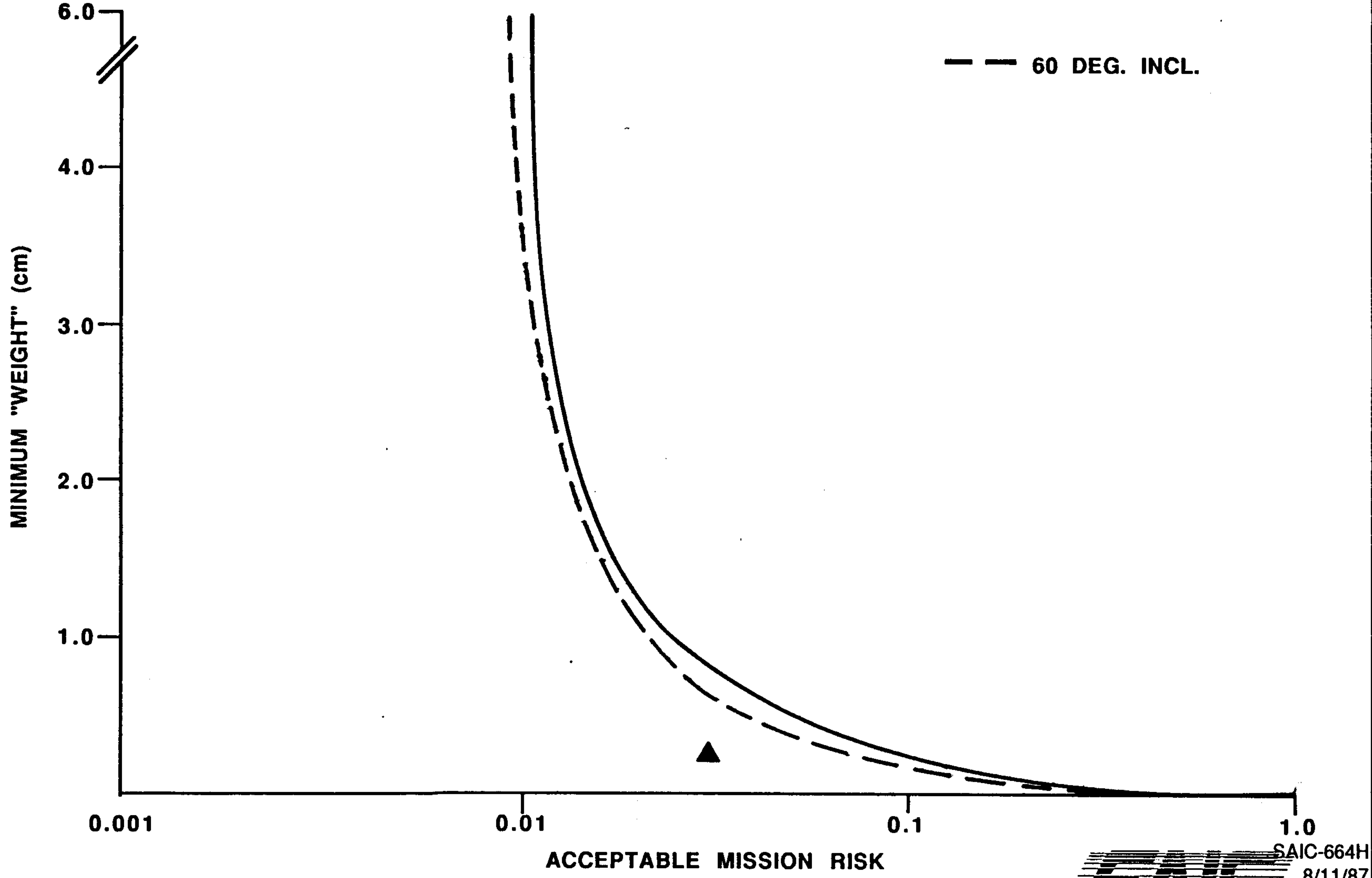
# SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN PROBABILITY OF NO PENETRATION: BOEING PREDICTOR




SAIC-664H
8/11/87

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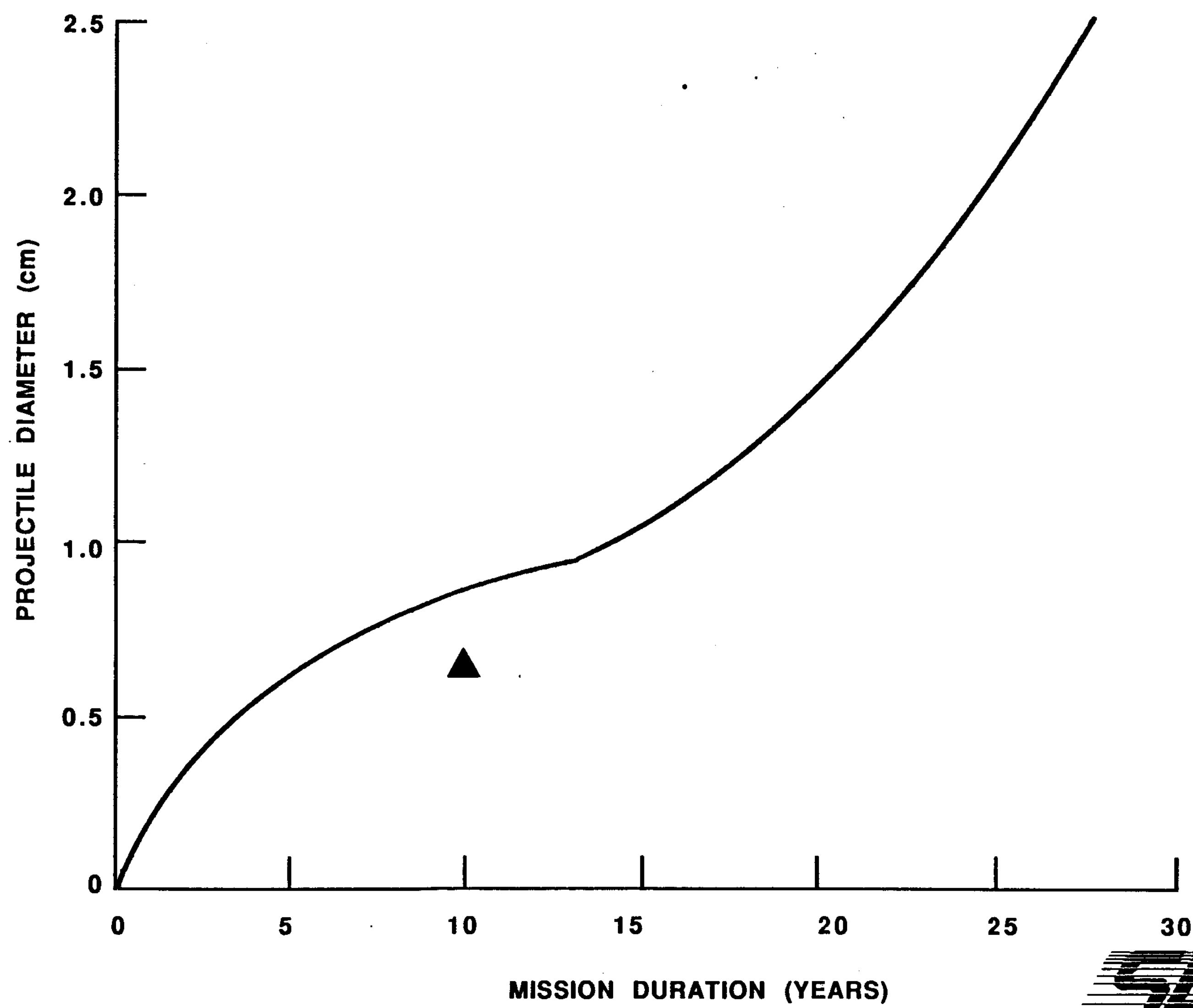
# EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER

**THE EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER IS SHOWN FOR THE DEBRIS SCENARIO. NOTE THE INFLECTION AT ABOUT 15 YEARS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE AT A PROJECTILE DIAMETER OF 1 CM.**

# EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER

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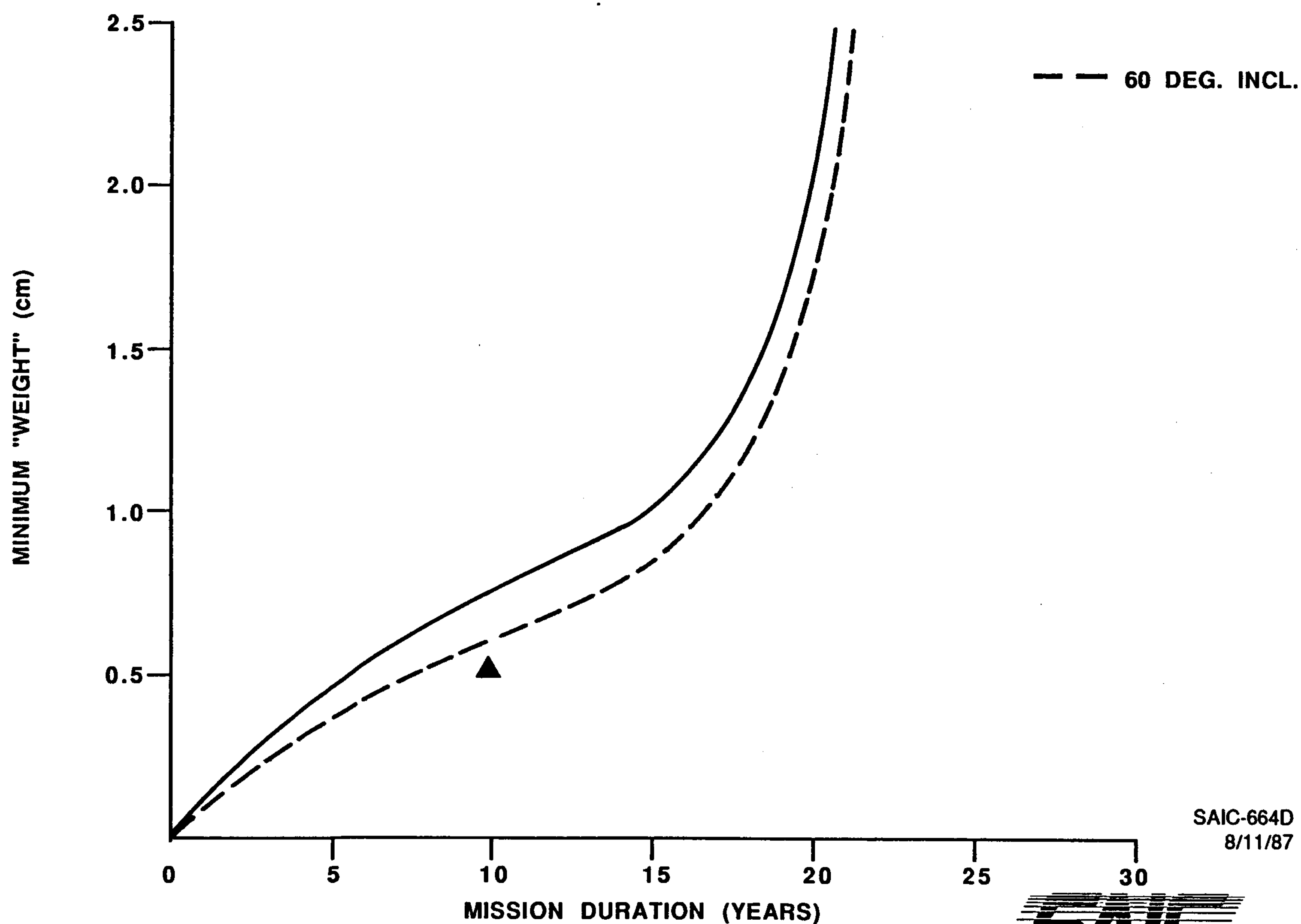
## SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR

SHOWN IS THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCLINATIONS. THE INFLECTION AT 15 YEARS, AND THE SHARP INCREASE IN SLOPE AT ABOUT 22 YEARS RAISES SERIOUS DESIGN QUESTIONS ABOUT LONG-DURATION MISSIONS FOR MISSION PLANNERS.

## SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR




SAIC-664D
8/11/87

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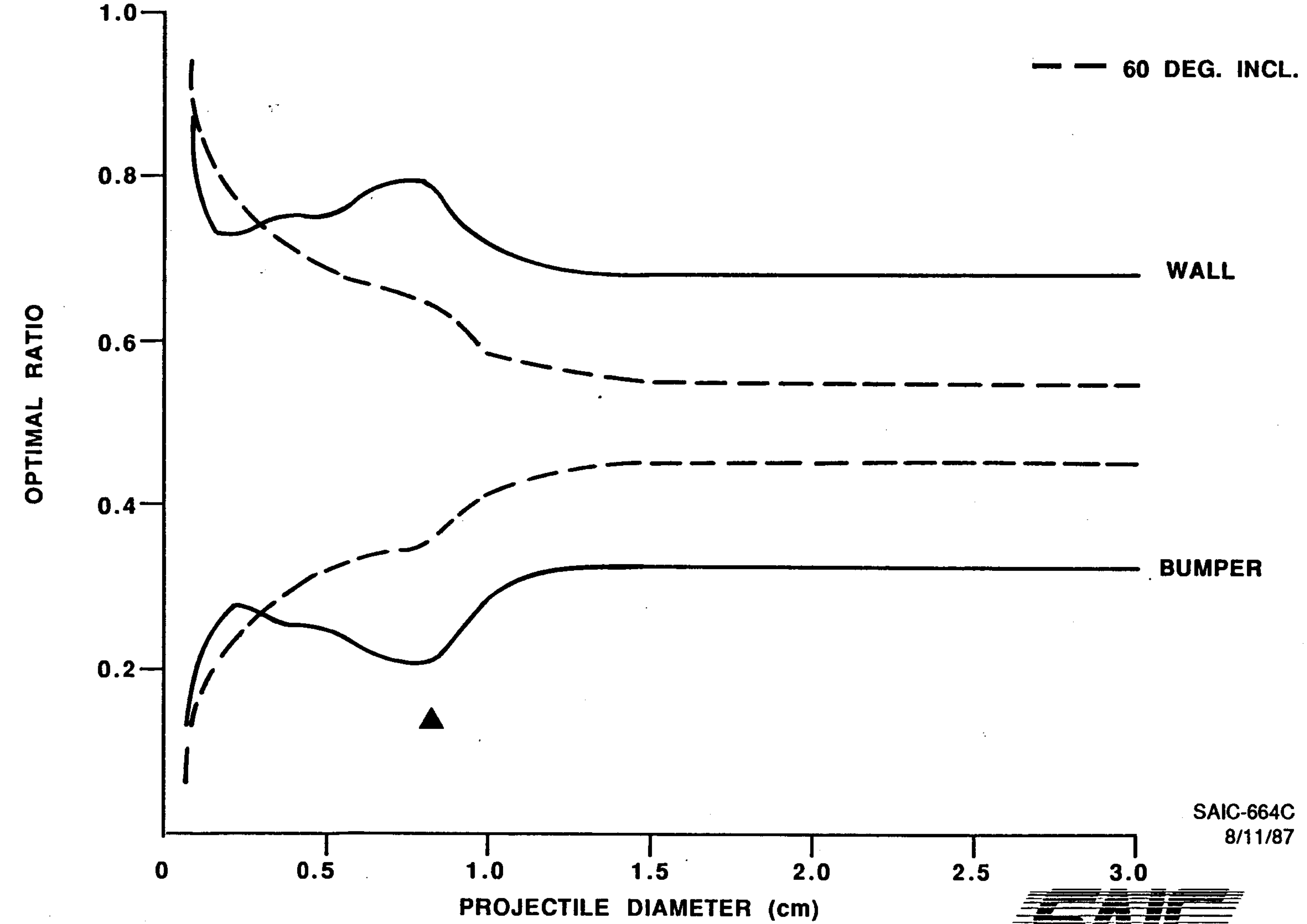
# GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NONLINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS. NOTE THAT A 60 DEGREE INCLINATION TENDS TO EVEN OUT THE THICKNESS DISTRIBUTION BETWEEN BUMPER AND WALL, EXCEPT FOR SMALL PARTICLE DIAMETERS.

# GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR




SAIC-664C
8/11/87

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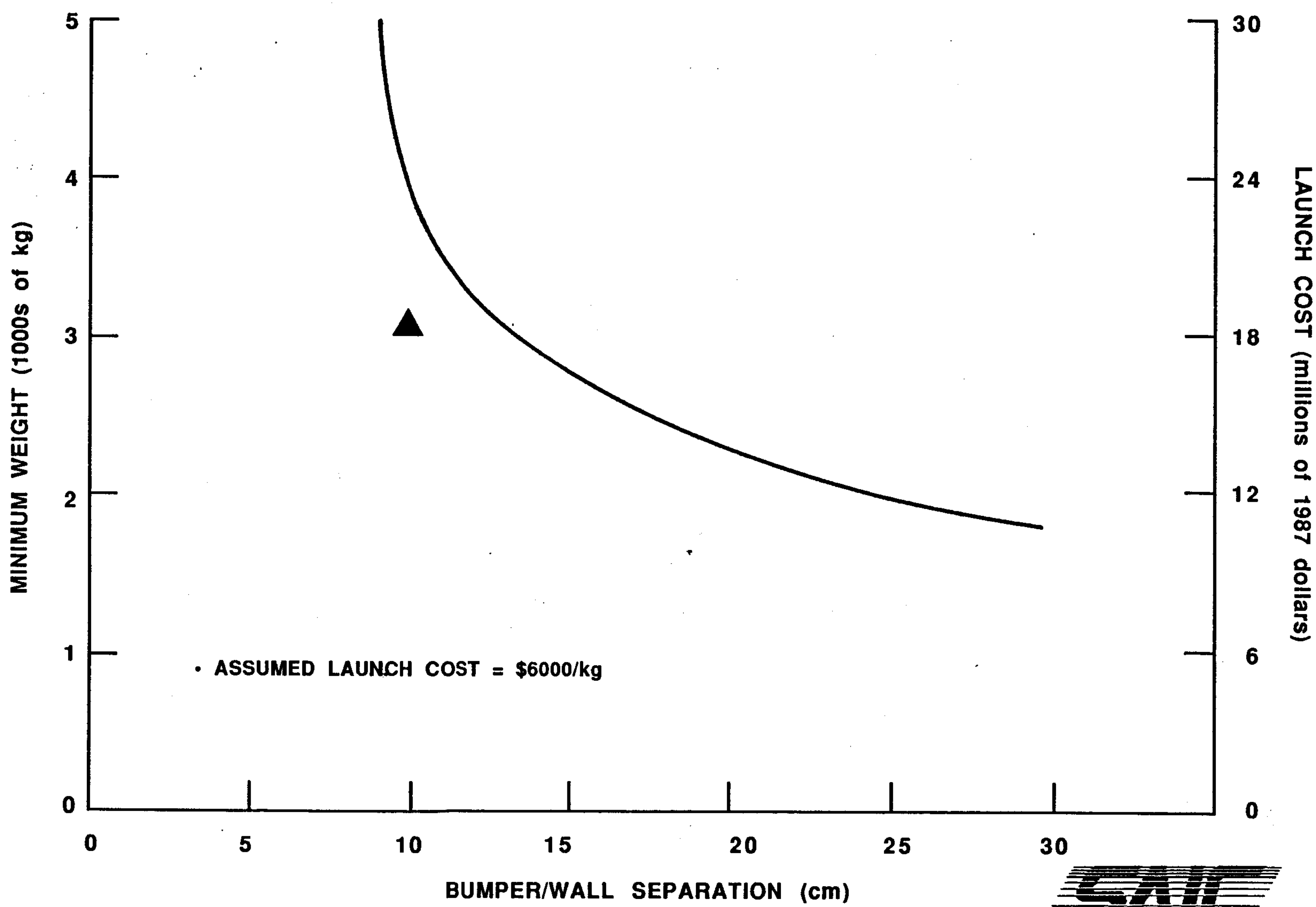
# DESIGNER'S COST EXCURSION

SHOWN IS THE EFFECT OF BUMPER/WALL SEPARATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS $6000/KG. BASED ON THIS ASSUMPTION, A SAVINGS OF ROUGHLY $7M (30%) IN LAUNCH COST IS INDUCED BY AN INCREASE IN SEPARATION FROM 10 TO 15 CM.

# DESIGNER'S COST EXCURSION



# MISSION PLANNER'S COST EXCURSION

THE EFFECT OF MISSION DURATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST IS SHOWN FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS $6000/KG. BASED ON THIS ASSUMPTION, AN INCREASE IN LAUNCH COST OF $37M (163%) IS INDUCED BY INCREASING THE MISSION DURATION FROM 10 TO 20 YEARS.



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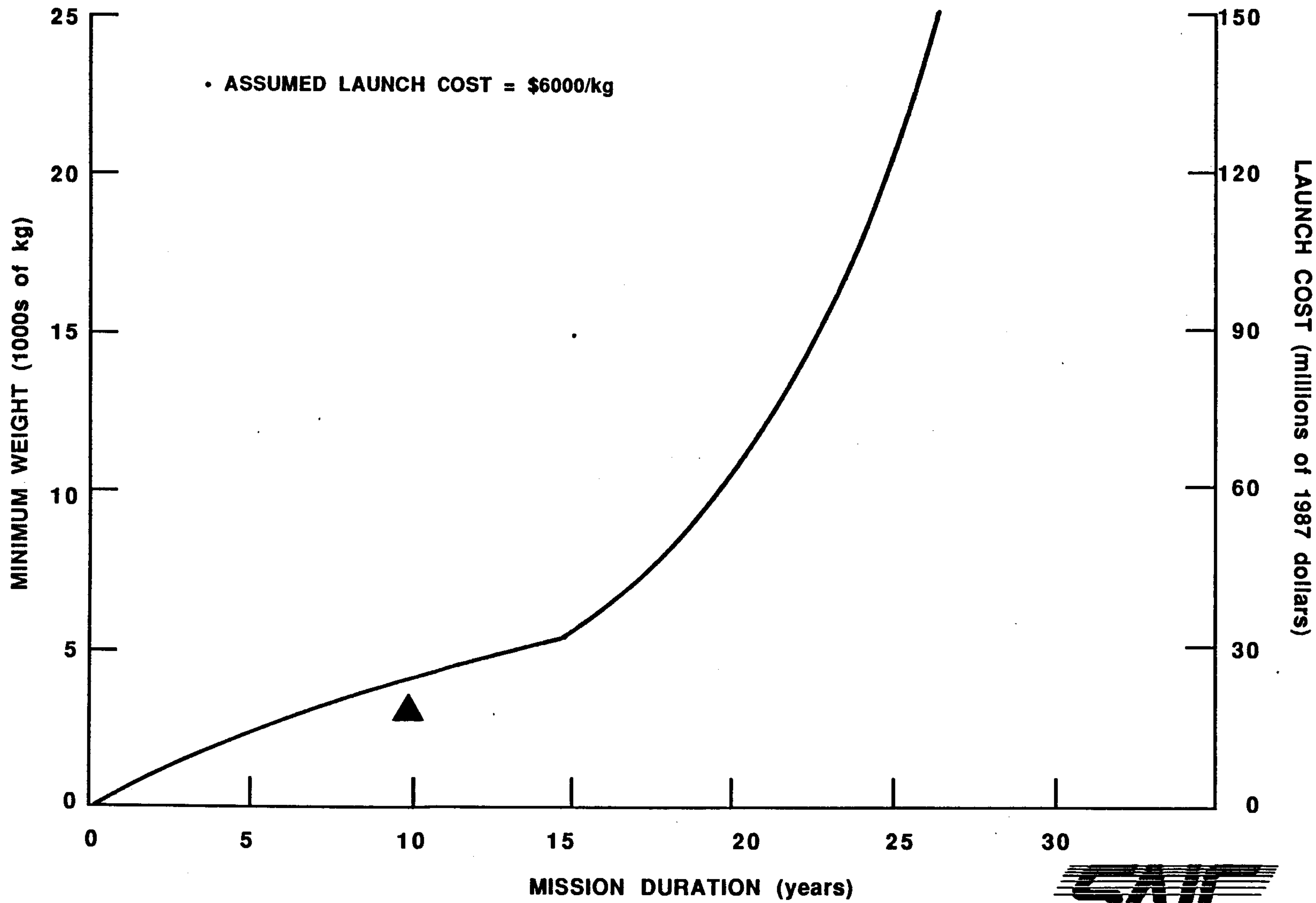
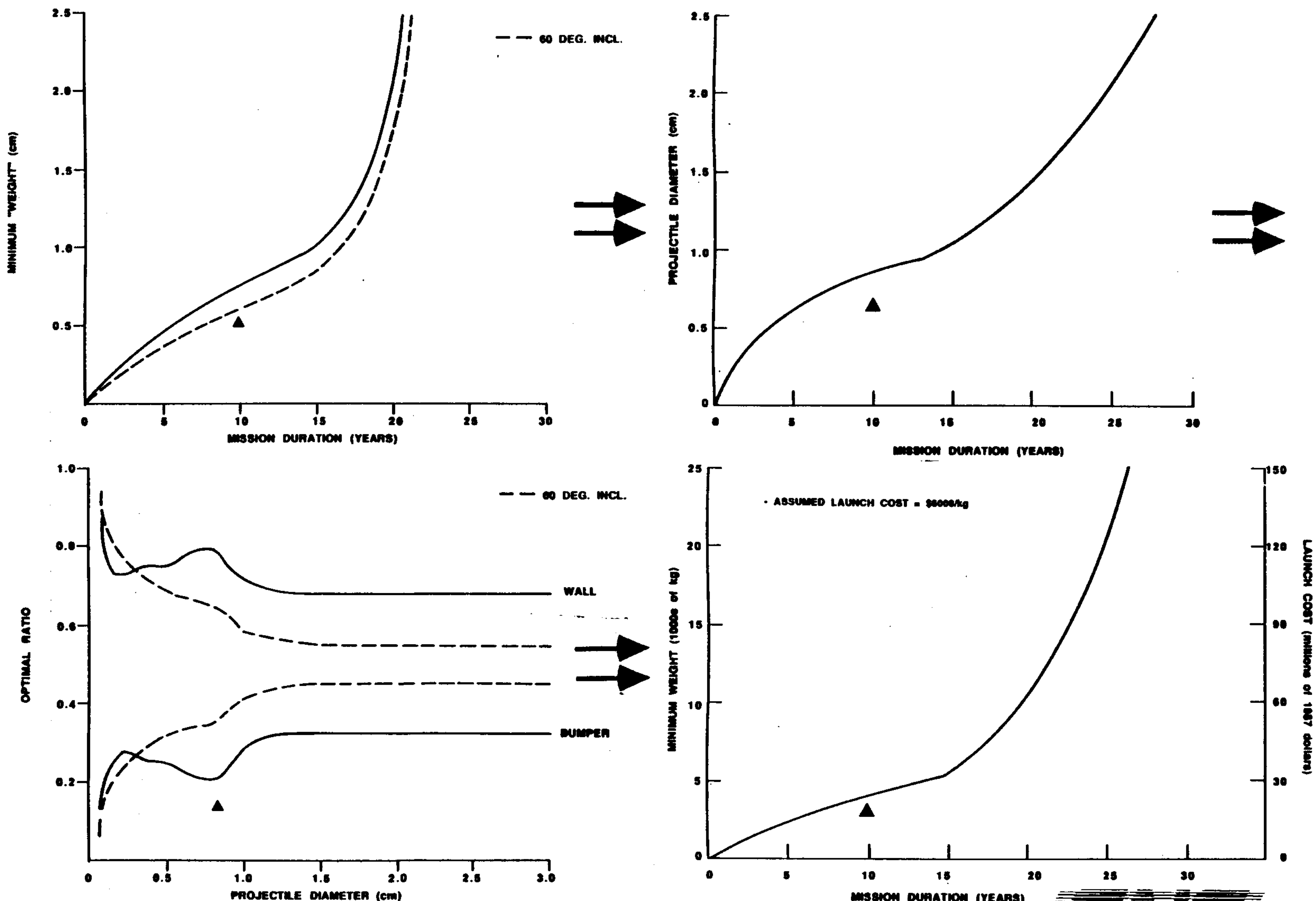
# MISSION PLANNER'S COST EXCURSION



# DETERMINING THE OPTIMAL PARAMETERS

AN EXAMPLE FOR DETERMINING THE OPTIMAL DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING PREDICTOR IS SHOWN. STARTING IN THE UPPER LEFT-HAND CORNER, IT IS DETERMINED THAT THE SUM OF THE MINIMUM BUMPER AND WALL THICKNESSES FOR A 10-YEAR MISSION (AND 30 DEGREE ORBITAL) INCLINATION IS ROUGHLY 0.75 CM. PROCEEDING TO THE RIGHT, ONE DETERMINES THE CRITICAL PROJECTILE DIAMETER TO BE APPROXIMATELY 0.85 CM. THIS CORRESPONDS TO AN OPTIMAL DISTRIBUTION OF 20% BUMPER, 80% WALL IN THE LOWER LEFT-HAND CORNER. THUS, THE OPTIMAL DESIGN THICKNESSES ARE DETERMINED TO BE ROUGHLY 0.15 CM FOR THE BUMPER, AND 0.60 CM FOR THE WALL. FINALLY, THE ACTUAL WEIGHT OF APPROXIMATELY 4000Kg AND COST OF ROUGHLY $24M ARE DETERMINED FROM THE LOWER RIGHT-HAND CHART.

# DETERMINING THE OPTIMAL PARAMETERS



# SUMMARY OF PREDICTOR RESULTS

SHOWN ARE THE OPTIMAL THICKNESSES FOR THE BASELINE PARAMETERS FOR EACH OF THE FIVE PREDICTORS INVESTIGATED IN THIS STUDY. IT IS INTERESTING TO NOTE THE DIVERSITY OF TOTAL THICKNESSES AND THICKNESS DISTRIBUTIONS FOR THESE CASES. NOTE ALSO THAT THE NYSMITH AND VELOCITY-INTEGRATED BOEING PREDICTORS BOTH ACHIEVE THE SAME TOTAL THICKNESSES, ALTHOUGH IN DIFFERENT PROPORTIONS.

BM06-9/9

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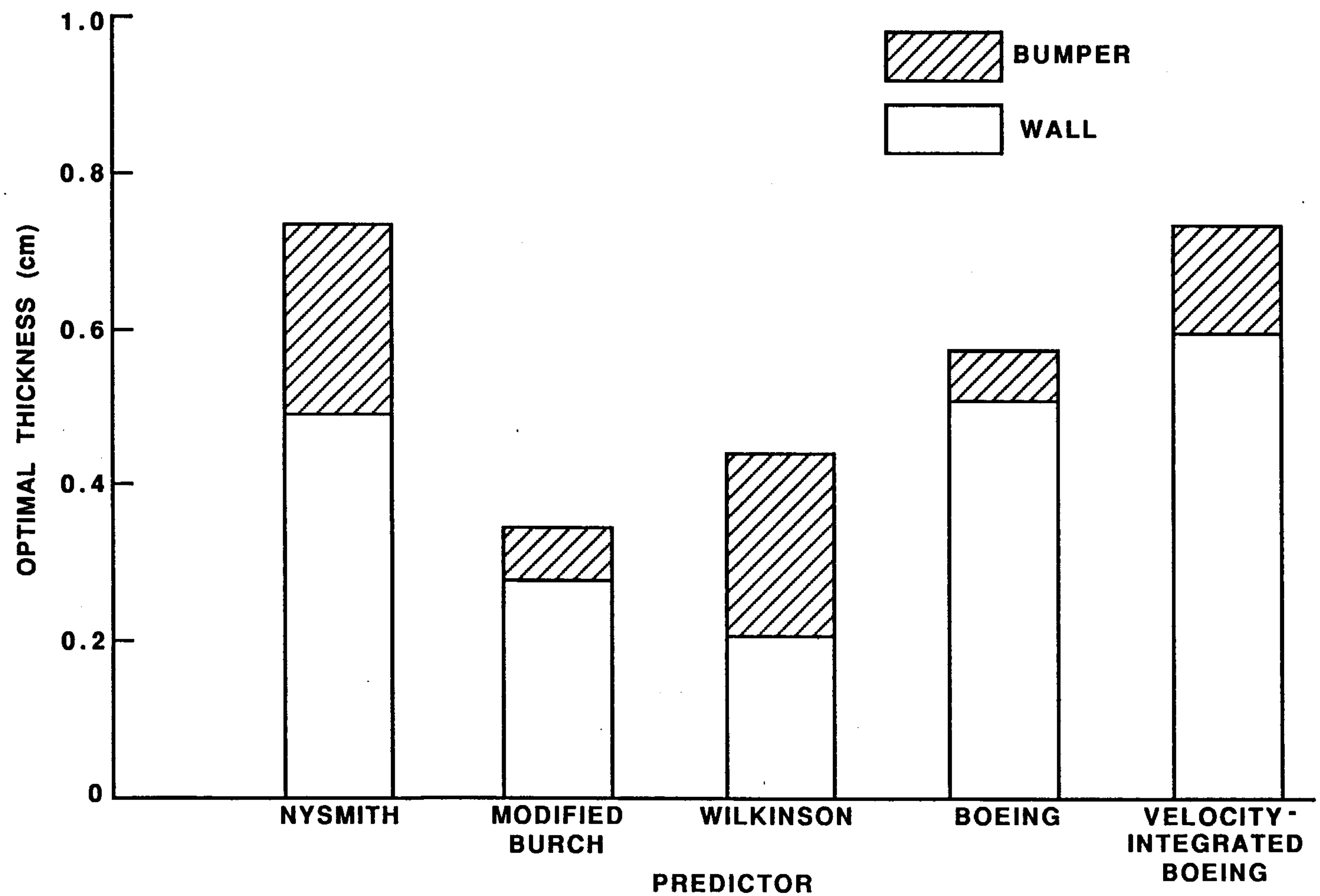
## SUMMARY OF PREDICTOR RESULTS

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# SECTION VII CONCLUSIONS

## GEOMETRIC PROGRAMMING CONCLUSIONS

- GEOMETRIC PROGRAMMING (GP) IS SUPERIOR TO THE EXTREMA THEOREM (ET) FOR THOSE IMPACT PROBLEMS WHERE BOTH METHODS ARE APPLICABLE
- THIS SUPERIORITY INCREASES WITH INCREASING DESIGN COMPLEXITY
- REDUCTION OF THE GEOMETRIC PROGRAMMING PROBLEM FROM 5 DEGREES-OF-DIFFICULTY TO 2 RESULTS IN NEGLIGIBLE DESIGN ERROR (PROVIDED BUMPER AND WALL THICKNESSES REMAIN SMALL IN COMPARISON TO MODULE RADIUS)
- OPTIMAL DESIGN DETERMINED FROM SPECIFIC MODULE CONFIGURATION IS NO DIFFERENT THAN FROM IDEALIZED SCENARIO.
- GEOMETRIC PROGRAMMING APPLIES TO NONLINEAR, FUNCTIONAL, PIECE-WISE CONTINUOUS (E.G., WILKINSON) PREDICTORS IN POSYNOMIAL FORM
- SINCE IMPACT PREDICTOR INDEPENDENT VARIABLES ARE INHERENTLY POSITIVE-VALUED, THE ONLY POTENTIAL DOWNFALL FOR GEOMETRIC PROGRAMMING IS NEGATIVE COEFFICIENTS.
- THE BURCH PREDICTOR IS EASILY MODIFIED TO SATISFY THE POSYNOMIAL REQUIREMENT
- THE PEN4 PREDICTOR MAY NOT BE EASILY MODIFIED TO SATISFY THE POSY-NOMIAL REQUIREMENT.

BM11-9/9

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# SECTION VII CONCLUSIONS (CONT'D)

## NYSMITH PREDICTOR CONCLUSIONS

- THE NYSMITH PREDICTOR HAS A THIRD INEQUALITY CONSTRAINT WHICH LIMITS ITS USAGE.
- THE COMPUTER SOLUTION REGION FOR THE NYSMITH PREDICTOR IS NARROW ENOUGH (FOR MOST PROBLEMS) TO BE APPROXIMATED ANALYTICALLY.
- THE NYSMITH PREDICTOR IMPLIES AN OPTIMAL THICKNESS DISTRIBUTION OF 35% BUMPER AND 65% WALL.
- THE NYSMITH PREDICTOR REQUIRES OPTIMAL BALLISTIC LIMIT THICKNESSES ROUGHLY 1.5 TIMES CURRENT DESIGN (FOR THE BASELINE DESIGN PARAMETERS)
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE CORE MODULE CONFIGURATION.
- INCREASING THE BASELINE $P_0$ HEAVILY TAXES THE DESIGN.
- A 50% INCREASE IN THE BASELINE BUMPER/WALL SEPARATION PROVIDES A 30% DECREASE IN THE TOTAL DESIGN THICKNESS.
- THE NYSMITH PREDICTOR SHOWS LITTLE DESIGN SENSITIVITY TO PROJECTILE VELOCITY.
- DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION.

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# SECTION VII CONCLUSIONS (CONT'D)

## BOEING SUBPREDICTOR CONCLUSIONS

- THE PEN4 PREDICTOR SHOWS NO DEPENDENCY ON BUMPER/WALL SEPARATION
- THE PEN4 PREDICTOR IS NOT VALID FOR VELOCITIES ABOVE ROUGHLY 2.8 KM/SEC
- ONE LOCAL OPTIMAL DESIGN DISTRIBUTION FOR THE PEN4 PREDICTOR IS 100% BUMPER, 0% WALL
- THE BURCH PREDICTOR SHOWS NO DEPENDENCY ON PROJECTILE OR WALL MATERIAL PROPERTIES
- THE MODIFIED BURCH PREDICTOR APPROXIMATES THE BURCH MODEL WELL
- THE MODIFIED BURCH MINIMUM "WEIGHT" IS INVERSELY PROPORTIONAL TO PROJECTILE VELOCITY
- THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE MODIFIED BURCH AND WILKINSON PREDICTORS
- THE WILKINSON PREDICTOR SHOWS MORE SENSITIVITY TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, MISSION RISK, AND MISSION DURATION THAN THE MODIFIED BURCH PREDICTOR
- OPTIMAL RATIOS ARE FAIRLY CONSTANT FOR ALL 3 BOEING SUBPREDICTORS

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# SECTION VII CONCLUSIONS (CONT'D)

## BOEING PREDICTOR CONCLUSIONS

- THE BOEING PREDICTOR IS A COMPLEX PIECEWISE CONTINUOUS PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES THE DESIGN FOR THE BOEING PREDICTOR
- THE OPTIMAL DESIGN AS A FUNCTION OF PROJECTILE VELOCITY IS NOT MONOTONIC
- THE BOEING PREDICTOR SHOWS SHARP SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK AND DURATION
- THE OPTIMAL RATIO FOR THE BOEING PREDICTOR IS ALSO NOT MONOTONIC AND IS FAIRLY SENSITIVE TO SMALL PROJECTILE DIAMETERS



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# SECTION VII CONCLUSIONS (CONT'D)

## VELOCITY-INTEGRATED BOEING PREDICTOR CONCLUSIONS

- UNDER THESE ASSUMPTIONS, A 60 DEGREE ORBITAL INCLINATION IS PREFERABLE TO A 30 DEGREE ONE FOR THE BOEING PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN
- THIS PREDICTOR SHOWS STRONG SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK, AND DURATION
- THE OPTIMAL RATIO FOR THE VELOCITY-INTEGRATED PREDICTOR IS MONOTONIC FOR A 60 DEGREE ORBITAL INCLINATION, BUT NOT FOR A 30 DEGREE ONE

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# SECTION VIII RECOMMENDATIONS

- EVALUATION OF BURCH, BOEING, AND VELOCITY-INTEGRATED BOEING PREDICTORS FOR NON-NORMAL IMPACTS
- COMPARISON OF RESULTS WITH BOEING'S BUMPER CODE
- FULL DESIGN TRADE EVALUATIONS FOR MADDEN, RICHARDSON, AND OTHER AVAILABLE PREDICTORS
- PREDICTOR/TEST DATA CORRELATION
- DESIGN GENERALIZATION TO INCLUDE CONSTRAINTS RELATED TO PRESSURE, THERMAL, STRESS, RADIATION, CONTAMINATION, AND OTHER EFFECTS AS APPLICABLE
- APPLICATION OF THIS DESIGN METHODOLOGY TO SPACE STATION COMPONENTS OTHER THAN CORE MODULE CONFIGURATION (E.G., TANKS, OMV, OTV)
- APPLICATION OF THIS DESIGN METHODOLOGY TO OTHER PROGRAMS (E.G., DEEP SPACE PROBES, PLANETARY MISSIONS, TRANSFER VEHICLES, SPACEPORTS)

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# SECTION VIII RECOMMENDATIONS (CONT'D)

- COMPUTER CODE DEVELOPMENT TO ANALYZE GENERIC PREDICTORS
- EVALUATION OF EFFECT OF EVOLVING SPACE DEBRIS ENVIRONMENT ON DESIGN
- EVALUATION OF EFFECT OF CHANGES IN CMC DESIGN ON OPTIMAL THICKNESSES
- COMPUTER PLOTTING POST-PROCESSOR FOR RAPID DISPLAY OF DESIGNER TRADEOFFS

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# SECTION IX

## REFERENCES

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# SECTION X

## APPENDICES

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# A. MATHEMATICS

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## GP APPLIED TO NYSMITH

Consider the Nysmith Equation:

$$t_2 = 5.08V^{.278}d^{2.92}/(t_1^{0.528}h^{1.39}) \ ,$$

with inequality constraints

$$t_1/d \le 0.5 \ , \ t_2/d \le 1.0$$

Note that if

$$d > 0.24hV^{-0.2} \ , \text{ then}$$

$$\frac{t_1}{d} \le 0.5 \Rightarrow$$

$$\frac{t_2}{d} > 5.08V^{.278}(0.24hV^{-0.2})^{1.39}/[(0.5)^{.528}h^{1.39}] \quad \text{or ,}$$

$$\frac{t_2}{d} > 1.0$$

Therefore, the third inequality constraint of Nysmith may be written:

$$\boxed{d \le 0.24hV^{-0.2}}$$

Letting the idealized "weight" be denoted by $w$ , one has:

$$w = t_1 + t_2$$

Substituting Nysmith, one has:

$$w = t_1 + 5.08V^{.278}d^{2.92}/(t_1^{.528}h^{1.39}) \ ,$$

with inequality constraints:

$$\frac{2t_1}{d} \le 1.0 \ , \ 5.08V^{.278}d^{1.92}/(t_1^{.528}h^{1.39}) \le 1.0$$

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### A. Unconstrained Optimization

The dual GP problem may be written:

maximize: $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$

subject to: $\delta_1 + \delta_2 = 1$

$\delta_1 - 0.528\delta_2 = 0$

where: $c_1 = 5.08V^{.278} d^{2.92} / h^{1.39}$

This is easily solved, giving:

$\delta_1 = 0.35$ , $\delta_2 = 0.65$ ,

| | |
|---|---|
| $w_0 = 5.52V^{.18} d^{1.91} / h^{0.91}$ | is the minimum "weight". |
| $t_{1_0} = 1.93V^{.18} d^{1.91} / h^{0.91}$ | is the optimal bumper thickness, and |
| $t_{2_0} = 3.59V^{.18} d^{1.91} / h^{0.91}$ | is the optimal wall thickness. |

Note that the optimal ratios are given by:

$$\frac{t_{1_0}}{t_{1_0} + t_{2_0}} = 0.35 = \delta_1 \quad , \quad \frac{t_{2_0}}{t_{1_0} + t_{2_0}} = 0.65 = \delta_2$$

Furthermore, this analytic solution is valid for

$d \le 0.23hV^{-0.2}$ Why?

$h \ge 4.35dV^{0.2} \Rightarrow t_{1_0} \le 1.93V^{.18} d^{1.91} (4.35dV^{0.2})^{-0.91}$ or

$t_{1_0} \le 0.5d$ , as desired. Also,

$t_{2_0} = 1.86t_{1_0} < d$ , as required.

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Thus the constrained problem need only be solved for

$$\boxed{0.23hV^{-0.2} \le d \le 0.24hV^{-0.2}}$$

**B. Constrained Optimization**

The constrained dual GP problem may be written:

maximize: $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2} (c_3)^{\delta_{11}'} (c_4)^{\delta_{12}'}$

subject to: $\delta_1 + \delta_2 = 1$

$\delta_1 - 0.528\delta_2 + \delta_{11}' - 0.528\delta_{12}' = 0$

where: $c_1$ is defined as in part A

$c_2 = c_1/d$

$c_3 = 2/d$

This is a 2 degree-of-difficulty problem, since there are 2 equations and 4 unknowns. It is solved numerically.

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## DERIVATION OF CORE MODULE CONFIGURATION WEIGHT

Let: $r_{12} =$ radius of a core module

$r_{22} = r_{12} + t_2$

$r_{11} = r_{22} + h$

$r_{21} = r_{11} + t_1$

$L =$ core module length

Then,

$$w = \pi L[\rho_1(r_{21}^2 - r_{11}^2) + \rho_2(r_{22}^2 - r_{12}^2)]$$

is the total core module weight.

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## GP APPLIED TO THE CMC WEIGHT FUNCTION

Let: $r_{12} = 210.8$ cm

$L = 1356.7$ cm

$\rho_1 = \rho_2 = 2.81$ gm/cm$^3$

Applying the Nysmith equation, one has:

$$w_{CMC} = 12t_1^2 + c_1t_1 + 122c_2t_1^{0.472} + 25700c_2t_1^{-0.528} + 310c_2^2t_1^{-1.06}$$

where:

$c_1 = 5059 + 24h$ , and

$c_2 = V^{.278}d^{2.92}/h^{1.39}$

The chosen approximate weight is given by:

$$w_{CMC_{Approx}} = c_1t_1 + 25700c_2t_1^{-0.528}$$

The unconstrained GP problem is then:

maximize: $$v(\delta) = (c_1/\delta_1)^{\delta_1}\left(\frac{25700c_2}{\delta_2}\right)^{\delta_2}$$

subject to: $$\delta_1 + \delta_2 = 1$$

$$\delta_1 - .528\delta_2 = 0$$

This is easily solved yielding:

$\delta_1 = 0.346$ , $\delta_2 = 0.654$

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$$w_0 = 1459 c_1^{0.346} c_2^{0.654}$$

$$t_{1_0} = \frac{\delta_1 w_0}{c_1} = 505\left(\frac{c_2}{c_1}\right)^{0.654}$$

$$t_{2_0} = 1.89 t_{1_0} = 954\left(\frac{c_2}{c_1}\right)^{0.654}$$

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## GP APPLIED TO WILKINSON

Recall that:

$$\frac{D\rho_p}{\rho_1 t_1} \le 1 \Rightarrow \quad t_2 = 0.364 D^3 \rho_p V_N / (L_2 S^2 \rho_2) \quad \text{and ,}$$

$$\frac{D\rho_p}{\rho_1 t_1} > 1 \Rightarrow \quad t_2 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 t_1 \rho_2)$$

Consider the case where:

$$\frac{D\rho_p}{\rho_1 t_1} > 1$$

Then, $w = t_1 + c_1 t_1^{-1}$ is the idealized weight.

Where:

$$c_1 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 \rho_2)$$

The dual GP problem may be written:

maximize: $\quad v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$

subject to: $\quad \delta_1 + \delta_2 = 1$

$$\delta_1 - \delta_2 = 0$$

Thus, $\delta_1 = \delta_2 = 1/2$ , and

$$\boxed{w_0 = 1.207 \frac{D^2 \rho_p}{S} \left( \frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}}$$

$$\boxed{t_{1_0} = t_{2_0} = 0.604 \frac{D^2 \rho_p}{S} \left( \frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}}$$

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Thus, the procedure is the following:

1) Determine $t_{1_0}$ , $t_{2_0}$ from the above equation.

2) Compute $\dfrac{D\rho_p}{\rho_1 t_{1_0}}$ .

3) If $\dfrac{D\rho_p}{\rho_1 t_{1_0}} > 1$ , then quit. Optimal design is $\left(t_{1_0}, t_{2_0}\right)$.

4) If $\dfrac{D\rho_p}{\rho_1 t_{1_0}} \leq 1$ , optimal design is $\left(t_{1_0}, t_{2_0} / \left(\dfrac{D\rho_p}{\rho_1 t_{1_0}}\right)\right)$.

**Optimal Ratios for Wilkinson**

Recall that the optimal thickness distribution between bumper and wall is equal unless:

$$\frac{D\rho_p}{\rho_1 t_{1_0}} \leq 1 \text{ , or } t_{1_0} \geq \frac{D\rho_p}{\rho_1} .$$

This implies:

$$0.604 \frac{D^2 \rho_p}{S} \left(\frac{V_N}{L_2 \rho_1 \rho_2}\right)^{1/2} \geq \frac{D\rho_p}{\rho_1} \text{ , or}$$

$$\boxed{D \geq 1.66 s \left(\frac{L_2 \rho_2}{V_N \rho_1}\right)^{1/2}}$$

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## GP APPLIED TO MODIFIED BURCH

Recall the Modified Burch Predictor:

$t_2 = \overline{C}\,\overline{K}$ , where

$$\overline{C} = \left(\frac{D}{N}\right)^{1.71}\left(\frac{C}{V}\right)^{2.29} / S^{0.71}$$ , and

$$\overline{K} = 2.8(t_1/D)^{0.57} + 1.58(t_1/D)^{-0.57}$$

Thus,

$w = t_1 + 2.8\overline{C}D^{-0.57}t_1^{0.57} + 1.58\overline{C}D^{0.57}t_1^{-0.57}$ is the idealized weight.

Thus, the GP dual problem may be written:

Maximize: $$v(\delta) = \left(\frac{1}{\delta_1}\right)^{\delta_1}\left(\frac{2.8\overline{C}D^{-0.57}}{\delta_2}\right)^{\delta_2}\left(\frac{1.58\overline{C}D^{0.57}}{\delta_3}\right)^{\delta_3}$$

Subject to: $\delta_1 + 0.57\delta_2 - 0.57\delta_3 = 0$ , and

$$\delta_1 + \delta_2 + \delta_3 = 1$$

Thus, we have:

$\delta_2 = 2.33(1 - 1.57\delta_3)$ , $\delta_1 = 1.33(2\delta_3 - 1)$ ,

and since $\delta_1 > 0$ , $\delta_2 > 0$ , we have $0.5 < \delta_3 < 0.64$ .

This is a one degree-of-difficulty problem with the following procedure:

1) Vary $\delta_3$ from 0.5 to 0.64 to find the max $v(\delta)$ .

2) Using the corresponding $\delta_3$ , solve for $\delta_1$ , $\delta_2$ .

3) Let $t_{1_0} = \delta_1(\max(v(\delta)))$ .

4) Let $t_{2_0} = \max(v(\delta)) - t_{1_0}$ .

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## OPTIMAL DESIGN ALGORITHM FOR BOEING PREDICTOR

1. Compute optimal design for PEN4 Predictor, $\left(t_{1_{0_P}}, t_{2_{0_P}}\right)$.

2. Check against PEN4 constraint, $V \le V_f\left[t_{1_{0_P}}/D\right] + 4000$ ?

3. If satisfied, the optimal design is $\left(t_{1_0}, t_{2_0}\right) = \left(t_{1_{0_P}}, t_{2_{0_P}}\right)$.

4. Else, compute optimal designs for Modified Burch, $\left(t_{1_{0_B}}, t_{2_{0_B}}\right)$, and Wilkinson, $\left(t_{1_{0_W}}, t_{2_{0_W}}\right)$ Predictors.

5. Compute Wilkinson wall induced by optimal Modified Burch bumper, $t_{2_W}\left(t_{1_{0_B}}\right)$.

6. Compute Burch wall induced by optimal Wilkinson bumper, $t_{2_B}\left(t_{1_{0_W}}\right)$.

7. Find $\left(t_{1_0}, t_{2_0}\right) = \min_{t_1 + t_2}\left[\left(t_{1_{0_B}}, \max\left(t_{2_{0_B}}, t_{2_W}\left(t_{1_{0_B}}\right)\right)\right), \left(t_{1_{0_W}}, \max\left(t_{2_{0_W}}, t_{2_B}\left(t_{1_{0_W}}\right)\right)\right)\right]$.

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# B. COMPUTER CODES

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# METEOR1

METEOR1 is the meteoroid environment model (see Survivability and Predictor Reference 1) used in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

METEOR1 takes as inputs the spacecraft exposed surface area, the mission duration, probability of no penetration and altitude, and the particle density. METEOR1 accounts for Earth shielding and gravitational defocussing factors. The output is the critical projectile diameter. A sample input (MET.IN), output (MET.OUT) and program listing (METEOR1.LIS) follow.

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```
1           !NO. OF CASES
400.        !SURFACE AREA IN SQ. METERS
10.         !DURATION IN YEARS
.97         !PROB. OF NO PENETRATION
500.        !ALT. IN KM
.5          !DENSITY IN GM/CUBIC CM
```

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INPUT

```
SURFACE AREA IN SQUARE METERS =    400.0000
MISSION DURATION IN YEARS =    10.00000
PROB. OF NO PENETRATION =   0.9700000
ALTITUDE IN KILOMETERS =   500.0000
PROJ. DENSITY IN GM/CUBIC CM =   0.5000000
```

OUTPUT

```
DIAM=  0.4614225
```

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```
      OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='MET.IN')
      OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='MET.OUT')
      READ(9,*)NCASES
      DO 10 I=1,NCASES
         READ(9,*)SA
         READ(9,*)T
         READ(9,*)PO
         READ(9,*)ALT
         READ(9,*)DENS
         WRITE (10,*)'       INPUT'
         WRITE (10,*)
         WRITE(10,*)'      SURFACE AREA IN SQUARE METERS = ',SA
         WRITE(10,*)'      MISSION DURATION IN YEARS = ',T
         WRITE(10,*)'      PROB. OF NO PENETRATION = ',PO
         WRITE(10,*)'      ALTITUDE IN KILOMETERS = ',ALT
         WRITE(10,*)'      PROJ. DENSITY IN GM/CUBIC CM = ',DENS
         WRITE (10,*)
         WRITE (10,*)'       OUTPUT'
         WRITE (10,*)
         T=31536000.*T
         FLUX=-1.*ALOG(PO)/(SA*T)
         RA=6371./(6371.+ALT)
         GE=.568+.432*RA
         THETA=ATAN(6371./SQRT(ALT*(ALT+2.*6371.)))
         S=(1.+COS(THETA))/2.
         FLUX=FLUX/(GE*S)
         F=ALOG10(FLUX)
         IF(F.GE.-4.403)THEN
           WRITE(10,*)'      MASS IS TOO SMALL'
           GO TO 10
         ENDIF
         IF(F.GT.-7.103.AND.F.LT.-4.403)THEN
           RAD=2.509-.25*(14.339+L)
           XM=10.**((-1.584+SQRT(RAD))/.125)
         ENDIF
         IF(F.LE.-7.103.AND.F.GE.-14.37)THEN
           XM=10.**((14.37+F)/-1.213)
         ENDIF
         IF(F.LT.-14.37)THEN
           WRITE(10,*)'      MASS IS TOO LARGE'
           GO TO 10
         ENDIF
         D=(1.91*XM/DENS)**.333
         WRITE(10,*)'      DIAM=',D
10       CONTINUE
         END
```

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## DEBRIS1

DEBRIS1 is the space debris environment model (see Survivability and Predictor Reference 2) in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

DEBRIS1 takes as inputs the spacecraft projected debris area, the mission duration, probability of no penetration, and altitude (currently fixed at 500 Km). The output is the critical projectile diameter. A sample input (DEB.IN), output (DEB.OUT), and program listing (DEBRIS1.LIS) follow.

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```
1               !NO. OF CASES
574.            !PROJECTED AREA IN SQ. METERS
10.             !DURATION IN YEARS
.97             !PROB. OF NO PENETRATION
```

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INPUT

PROJ. AREA IN SQUARE METERS =    574.0000
MISSION DURATION IN YEARS =    10.00000
PROB. OF NO PENETRATION =   0.9700000

OUTPUT

DIAM=  0.8446254

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```
      OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='DEB.IN')
      OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='DEB.OUT')
      READ(9,*)NCASES
      DO 10 I=1,NCASES
         READ(9,*)AP
         READ(9,*)T
         READ(9,*)PO
         WRITE(10,*)'       INPUT'
         WRITE(10,*)
         WRITE(10,*)'       PROJ. AREA IN SQUARE METERS = ',AP
         WRITE(10,*)'       MISSION DURATION IN YEARS = ',T
         WRITE(10,*)'       PROB. OF NO PENETRATION = ',PO
         WRITE(10,*)
         WRITE(10,*)'       OUTPUT'
         WRITE(10,*)
         FLUX=-1.*ALOG(PO)/(AP*T)
         F=ALOG10(FLUX)
         IF(F.GE.-5.46)THEN
           D=10.**((F+5.46)/-2.52)
         ENDIF
         IF(F.LE.-7.0)THEN
           D=10.**((F-21.67)/-10.32)
         ENDIF
         IF(F.LT.-5.46.AND.F.GT.-7.0)THEN
           D=10.**((5.46+F)/-.63)
         ENDIF
         WRITE(10,*)'       DIAM=',D
10       CONTINUE
         END
```

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# IMPACT5

IMPACT5 is a spacecraft protective systems design optimization code. IMPACT5 employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, Burch, and PEN4 predictors. Inputs vary depending on the predictor used, however, typical inputs include projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5 is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. Sample input (IMPACT5.IN), output (IMPACT5.OUT) and program listing (IMPACT5.LIS) follow.

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6               !NUMBER OF CASES
1               !NYSMITH PREDICTOR
10.             !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIAMETER IN CM
10.             !BUMPER/WALL SEPARATION IN CM
2               !BOEING PREDICTOR
10.             !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
7344000.        !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.        !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3               !MADDEN PREDICTOR
10.             !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
2.81            !BUMPER/WALL DENSITY IN GM/CUBIC CM
4               !WILKINSON PREDICTOR
10.             !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
5               !BURCH PREDICTOR
10.             !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIA. IN CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
6               !PEN4 PREDICTOR
1.              !PROJ. VELOCITY IN KM/SEC
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
7344000.        !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.        !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.              !IMPACT ANGLE FROM NORMAL
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NYSMITH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2575910 CM
WALL THICKNESS = 0.4791193 CM
MIN. WEIGHT = 0.7367103 CM
CMC MIN. WEIGHT = 3799.036 KG

BOEING

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM
WALL THICKNESS = 0.4910776 CM
MIN. WEIGHT = 0.5831065 CM
CMC MIN. WEIGHT = 2978.630 KG

MADDEN

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3788331 CM
WALL THICKNESS = 0.3788331 CM
MIN. WEIGHT = 0.7576661 CM
CMC MIN. WEIGHT = 3934.167 KG

WILKINSON

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.2128253 CM
WALL THICKNESS = 0.2128253 CM
MIN. WEIGHT = 0.4256506 CM
CMC MIN. WEIGHT = 2208.558 KG

MODIFIED BURCH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM
WALL THICKNESS = 0.2539445 CM
MIN. WEIGHT = 0.3459734 CM
CMC MIN. WEIGHT = 1775.339 KG

PEN4

INPUT

PROJECTILE VELOCITY IN KM/SEC = 1.000000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00

OUTPUT

BUMPER THICKNESS = 2.1661645E-02CM

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WALL THICKNESS =   0.0000000E+00CM
MIN. WEIGHT =   2.1661645E-02CM
CMC MIN. WEIGHT =     222.9546    KG
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      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5.IN',ACCESS='SEQUENTIAL')
      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5.OUT',ACCESS='SEQUENTIAL')
      READ(10,*)NRUNS
      DO 10 I=1,NRUNS
        READ(10,*)NCODE
        IF(NCODE.EQ.1)GO TO 25
        IF(NCODE.EQ.2)GO TO 35
        IF(NCODE.EQ.3)GO TO 45
        IF(NCODE.EQ.4)GO TO 55
        IF(NCODE.EQ.5)GO TO 65
        IF(NCODE.EQ.6)GO TO 75
25      READ(10,*)V
        READ(10,*)D
        READ(10,*)H
        WRITE(11,*)'        NYSMITH'
        WRITE(11,*)
        WRITE(11,*)'        INPUT'
        WRITE(11,*)
        WRITE(11,*)'        PROJECTILE VELOCITY IN KM/SEC = ',V
        WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
        WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',H
        WRITE(11,*)
        CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
        WRITE(11,*)'        OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
35      READ(10,*)V
        READ(10,*)D
        READ(10,*)RHOP
        READ(10,*)RHO1
        READ(10,*)RHO2
        READ(10,*)S
        READ(10,*)XL2
        READ(10,*)SY1
        READ(10,*)SY2
        READ(10,*)THETA
        READ(10,*)XN
        READ(10,*)E1
        WRITE(11,*)'        BOEING'
        WRITE(11,*)
        WRITE(11,*)'        INPUT'
        WRITE(11,*)
        WRITE(11,*)'        PROJECTILE VELOCITY IN KM/SEC = ',V
        WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
        WRITE(11,*)'        PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
        WRITE(11,*)'        BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
        WRITE(11,*)'        WALL DENSITY IN GM/CUBIC CM = ',RHO2
        WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
        WRITE(11,*)'        WALL MATERIAL CONSTANT = ',XL2
        WRITE(11,*)'        BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
```

```
          WRITE(11,*)'      WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
          WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
          WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                              ' BUMPER = ',XN
          WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                         ' SEC = ',E1
          WRITE(11,*)
          CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &                XN,E1,T1,T2,WT,WTCMC)
          WRITE(11,*)'      OUTPUT'
          WRITE(11,*)
          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
   45     READ(10,*)V
          READ(10,*)D
          READ(10,*)RHOP
          READ(10,*)S
          READ(10,*)RHO
          WRITE(11,*)'      MADDEN'
          WRITE(11,*)
          WRITE(11,*)'      INPUT'
          WRITE(11,*)
          WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
          WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
          WRITE(11,*)'      BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
          WRITE(11,*)
          CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
          WRITE(11,*)'      OUTPUT'
          WRITE(11,*)
          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
   55     READ(10,*)V
          READ(10,*)D
          READ(10,*)RHOP
          READ(10,*)RHO1
          READ(10,*)RHO2
          READ(10,*)S
          READ(10,*)XL2
          WRITE(11,*)'      WILKINSON'
          WRITE(11,*)
          WRITE(11,*)'      INPUT'
          WRITE(11,*)
          WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
```

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OF POOR QUALITY

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          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
          WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
          WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
          WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RHO2
          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
          WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
          WRITE(11,*)
          CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
     &                T1,T2,WT,WTCMC)
          WRITE(11,*)'      OUTPUT'
          WRITE(11,*)
          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
65        READ(10,*)V
          READ(10,*)D
          READ(10,*)RHO1
          READ(10,*)S
          READ(10,*)THETA
          READ(10,*)XN
          READ(10,*)E1
*****    MODIFIED BURCH  *****
          WRITE(11,*)'      MODIFIED BURCH'
          WRITE(11,*)
          WRITE(11,*)'      INPUT'
          WRITE(11,*)
          WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
          WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
          WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
          WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                    ' BUMPER = ',XN
          WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                ' SEC = ',E1
          WRITE(11,*)
          WRITE(11,*)'      OUTPUT'
          WRITE(11,*)
          CALL BURCH(V,D,RHO1,S,THETA,
     &                XN,E1,T1,T2,WT,WTCMC)
          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
75        READ(10,*)V
          READ(10,*)D
          READ(10,*)RHOP
          READ(10,*)RHO1
```

```
              READ(10,*)RHO2
              READ(10,*)SY1
              READ(10,*)SY2
              READ(10,*)THETA
              WRITE(11,*)'          PEN4'
              WRITE(11,*)
              WRITE(11,*)'          INPUT'
              WRITE(11,*)
              WRITE(11,*)'          PROJECTILE VELOCITY IN KM/SEC = ',V
              WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D
              WRITE(11,*)'          PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
              WRITE(11,*)'          BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
              WRITE(11,*)'          WALL DENSITY IN GM/CUBIC CM = ',RHO2
              WRITE(11,*)'          BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
              WRITE(11,*)'          WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
              WRITE(11,*)'          IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
              WRITE(11,*)
              CALL PEN4(V,D,RHOP,RHO1,RHO2,SY1,SY2,THETA,
          &               T1,T2,WT,WTCMC)
              WRITE(11,*)'          OUTPUT'
              WRITE(11,*)
              WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
              WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
              WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
              WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
              WRITE(11,*)
              GO TO 10
      10      CONTINUE
              STOP
              END
```

```
      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
      DMAX=0.24*H*V**-0.2
      IF(D.GT.DMAX)THEN
        WRITE(11,*)'NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
        GO TO 16
      ENDIF
      T1=1.93*V**0.18*D**1.91/H**0.91
      T2=1.86*T1
      WT=T1+T2
      WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
      WTCMC=12.*WTCMC
16       CONTINUE
         RETURN
         END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 214 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 45 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 8 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 267 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | NYSMITH |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | DMAX | AP-0000000C@ | R*4 | H |
| AP-00000014@ | R*4 | T2 | AP-00000004@ | R*4 | V | AP-00000018@ | R*4 | WT |

LABELS

| Address | Label |
|---|---|
| 0-000000D5 | 16 |

```
      SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &            XN,E1,T1,T2,WT,WTCMC)
***** PEN4 *****
      T1=0.16
      V=V*3280.
      D=D/30.48
      RP=D/2.0
      RHOP=RHOP*1.94
      RHO1=RHO1*1.94
      RHO2=RHO2*1.94
      NITSP=0
      NITSP=NITSP+1
      NP1=0
      T1P=T1/30.48
      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
      WT=T1P+T2P
      IF(NITSP.EQ.1)THEN
        T1P1=1.1*T1P
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
      ENDIF
      IF(WT1.GT.WT)THEN
        T1P1=0.82*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
590     IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          T1P=T1P1
          T2P=T2P1
          WT=WT1
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          T1P1=0.9*T1P1
          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
          WT1=T1P1+T2P1
          GO TO 590
        ENDIF
      ELSE
579     T1P=T1P1
        T2P=T2P1
        WT=WT1
        T1P1=1.1*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
        IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          GO TO 579
```

```
             ENDIF
           ENDIF
  601      CONTINUE
           D=30.48*D
           RHOP=RHOP/1.94
           RHO1=RHO1/1.94
           RHO2=RHO2/1.94
           T1P=30.48*T1P
           T2P=30.48*T2P
           IF(T1P/D.LE.0.4)VF=4100
           IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
           VF=VF+4000.
           IF(V.LE.VF)THEN
             WRITE(11,*)'INSIDE OF PEN4 LIMITS'
             T1=T1P
             T2=T2P
             GO TO 1102
           ENDIF
  557      CONTINUE
  *****   WILKINSON  *****
           V=V/3280.
           T1=0.604*D**2.*RHOP/S
           T1=T1*SQRT(V/(XL2*RHO1*RHO2))
           RATIO=D*RHOP/(T1*RHO1)
           IF(RATIO.GT.1.0)T2=T1
           IF(RATIO.LE.1.0)T2=T1/RATIO
  *****   MODIFIED BURCH  *****
           VB=V*3280.
           DB=D/2.54
           CM=SQRT(E1/RHO1)
           CM=CM/30.48
           SB=S/2.54
           IF(THETA.LE.0.001)GO TO 125
           CHI=TAN(THETA)-0.5
           F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
           F2=F2+(1.7-12.*T1B/D)*CHI
           F3=0.32*(T1B/D)**0.83
           F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
           T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
           T2F=T2F*(D/S)**0.71
           T2N=F3*(CM/V)**1.33*D/XN
           IF(T2N.GE.T2F)T2B=T2N
           IF(T2N.LT.T2F)T2B=T2F
           T2B=T2B*2.54
           IF(T2B.GT.T2)NREGION=3
           IF(T2B.GT.T2)T2=T2B
           GO TO 155
  125      CONTINUE
           T1B1=T1/2.54
           NITSB=0
           XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
           VDELTA=0.0
           DELTA3=0.52
  1099     DELTA2=2.33*(1.-1.57*DELTA3)
           DELTA1=1.33*(2.*DELTA3-1.)
           VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
           VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

```
        IF(VDELTA1.LT.VDELTA)THEN
          DELTA1=1.33*(2.*DELTA3-1.04)
          T1B=DELTA1*VDELTA
          T2B=VDELTA-T1B
          GO TO 499
        ENDIF
        VDELTA=VDELTA1
        DELTA3=DELTA3+0.02
        IF(DELTA3.GT.0.63)THEN
          T1B=DELTA1*VDELTA
          T2B=VDELTA-T1B
          GO TO 499
        ENDIF
        GO TO 1099
499     CONTINUE
*****  COMPARISON OF MODIFIED BURCH AND WILKINSON  *****
199     CONTINUE
        T10W=T1/2.54
        F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
        T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
        T2BT10W=T2BT10W/SB**0.71
        T2BT10W=T2BT10W*2.54
        RATIOB=(DB*RHOP)/(RHO1*T1B)
        T2WT10B=0.364*D**3.*RHOP*V/(XL2*RHO2*S**2.)
        IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
        IF(T2BT10W.GT.T2)T2=T2BT10W
        T2B=T2B*2.54
        IF(T2WT10B.GT.T2B)T2B=T2WT10B
        T1B=T1B*2.54
        IF(T1B+T2B.LT.T1+T2)THEN
          T1=T1B
          T2=T2B
        ENDIF
155     CONTINUE
1102      IF(T2.LE.0.01)THEN
            WRITE(11,*)'PRESSURE CONSTRAINT ON WALL IN EFFECT'
            SIGMA=SY2/144.
            T2=3099.1/SIGMA
            ENDIF
        WT=T1+T2
        R12=211.
        R22=211.+T2
        R11=211.+T2+S
        R21=211.+T1+T2+S
        VB=4.27*(R21**2.-R11**2.)
        VW=4.27*(R22**2.-R12**2.)
        WTCMC=RHO1*VB+RHO2*VW
156     RETURN
        END
```

```
      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
      F1=F1-4.18
      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
      RETURN
      END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | $CODE | 163 | PIC | CON | REL | LCL | SHR | EXE | RD | NOWRT | LONG |
| 2 | $LOCAL | 4 | PIC | CON | REL | LCL | NOSHR | NOEXE | RD | WRT | LONG |
| | Total Space Allocated | 167 | | | | | | | | | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2B |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000010@ | R*4 | CM | AP-00000004@ | R*4 | DB | ** | R*4 | F1 |
| AP-00000008@ | R*4 | T1B | AP-00000014@ | R*4 | VB | AP-0000000C@ | R*4 | XN |

```
            FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
            A=1.33*RHOP*(V*RP)**2.
            B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
            C=1.33*RHOP*RP**2.0
            D1=RP*RHO1/COS(THETA)
            XK1=1.67*(RHOP/(2.*SY2))**0.31
            XK1=XK1*(0.281*D*RHOP/RHO2)**0.33
            XK1=XK1*COS(THETA)
            C1P1=(A-B*T1P)/(C+D1*T1P)
            IF(C1P1.LE.0.001)THEN
              FT2P=0.0
              GO TO 999
            ENDIF
            FT2P=XK1*C1P1**0.31
    999     RETURN
            END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 222 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 2 | $LOCAL | 4 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 226 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2P |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| ** | R*4 | A | ** | R*4 | B | ** | R*4 | C |
| AP-00000020@ | R*4 | D | ** | R*4 | D1 | AP-00000018@ | R*4 | RHO1 |
| AP-00000004@ | R*4 | RHOP | AP-0000000C@ | R*4 | RP | AP-00000010@ | R*4 | SY1 |
| AP-00000028@ | R*4 | T1P | AP-00000014@ | R*4 | THETA | AP-00000008@ | R*4 | V |

LABELS

| Address | Label |
|---|---|
| 0-000000D9 | 999 |

```
      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
      V=V*1.E05
      T1=0.009*SQRT(V)*RHOP*D**2.0
      T1=T1/(S*RHO**1.5)
      T2=T1
      WT=T1+T2
      R12=211.
      R22=211.+T2
      R11=211.+T2+S
      R21=211.+T1+T2+S
      VB=4.27*(R21**2.-R11**2.)
      VW=4.27*(R22**2.-R12**2.)
      WTCMC=RHO*(VB+VW)
      RETURN
      END
```

PROGRAM SECTIONS

| Name | Bytes | Attributes |
|---|---|---|
| 0 $CODE | 159 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| Total Space Allocated | 159 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | MADDEN |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | R11 | ** | R*4 | R12 |
| ** | R*4 | R22 | AP-00000014@ | R*4 | RHO | AP-0000000C@ | R*4 | RHOP |
| AP-00000018@ | R*4 | T1 | AP-0000001C@ | R*4 | T2 | AP-00000004@ | R*4 | V |
| ** | R*4 | VW | AP-00000020@ | R*4 | WT | AP-00000024@ | R*4 | WTCMC |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

```
        SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
     &                 T1,T2,WT,WTCMC)
        T1=0.604*D**2.*RHOP/S
        T1=T1*SQRT(V/(XL2*RHO1*RHO2))
        RATIO=D*RHOP/(T1*RHO1)
        IF(RATIO.GT.1.0)T2=T1
        IF(RATIO.LE.1.0)T2=T1/RATIO
        WT=T1+T2
        R12=211.
        R22=211.+T2
        R11=211.+T2+S
        R21=211.+T1+T2+S
        VB=4.27*(R21**2.-R11**2.)
        VW=4.27*(R22**2.-R12**2.)
        WTCMC=RHO1*VB+RHO2*VW
        RETURN
        END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 181 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| | Total Space Allocated | 181 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | WILKINSON |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | R11 | ** | R*4 | R12 |
| ** | R*4 | R22 | ** | R*4 | RATIO | AP-00000010@ | R*4 | RHO1 |
| AP-0000000C@ | R*4 | RHOP | AP-00000018@ | R*4 | S | AP-00000020@ | R*4 | T1 |
| AP-00000004@ | R*4 | V | ** | R*4 | VB | ** | R*4 | VW |
| AP-0000002C@ | R*4 | WTCMC | AP-0000001C@ | R*4 | XL2 | | | |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

```
*****  MODIFIED BURCH  *****
       SUBROUTINE BURCH(V,D,RHO1,S,THETA,
     &             XN,E1,T1,T2,WT,WTCMC)
       VB=V*3280.
       DB=D/2.54
       CM=SQRT(E1/RHO1)
       CM=CM/30.48
       SB=S/2.54
       IF(THETA.LE.0.001)GO TO 425
       CHI=TAN(THETA)-0.5
       F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
       F2=F2+(1.7-12.*T1B/D)*CHI
       F3=0.32*(T1B/D)**0.83
       F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
       T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
       T2F=T2F*(D/S)**0.71
       T2N=F3*(CM/V)**1.33*D/XN
       IF(T2N.GE.T2F)T2B=T2N
       IF(T2N.LT.T2F)T2B=T2F
       T2B=T2B*2.54
       IF(T2B.GT.T2)NREGION=3
       IF(T2B.GT.T2)T2=T2B
       GO TO 499
425    CONTINUE
       NITSB=0
       XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
       VDELTA=0.0
       DELTA3=0.52
1099   DELTA2=2.33*(1.-1.57*DELTA3)
       DELTA1=1.33*(2.*DELTA3-1.)
       VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
       VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
       IF(VDELTA1.LT.VDELTA)THEN
         DELTA1=1.33*(2.*DELTA3-1.04)
         T1=DELTA1*VDELTA
         T2=VDELTA-T1
         GO TO 499
       ENDIF
       VDELTA=VDELTA1
       DELTA3=DELTA3+0.02
       IF(DELTA3.GT.0.63)THEN
         T1=DELTA1*VDELTA
         T2=VDELTA-T1
         GO TO 499
       ENDIF
       GO TO 1099
499    CONTINUE
       T1=T1*2.54
       T2=T2*2.54
       WT=T1+T2
       R12=211.
       R22=211.+T2
       R11=211.+T2+S
       R21=211.+T1+T2+S
       VB=4.27*(R21**2.-R11**2.)
       VW=4.27*(R22**2.-R12**2.)
       WTCMC=RHO1*VB+2.81*VW
```

```
      SUBROUTINE PEN4(V,D,RHOP,RHO1,RHO2,SY1,SY2,THETA,
     &             T1,T2,WT,WTCMC)
      T1=0.16
      V=V*3280.
      D=D/30.48
      RP=D/2.0
      RHOP=RHOP*1.94
      RHO1=RHO1*1.94
      RHO2=RHO2*1.94
      NITSP=0
      NITSP=NITSP+1
      NP1=0
      T1P=T1/30.48
      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
      WT=T1P+T2P
      IF(NITSP.EQ.1)THEN
        T1P1=1.1*T1P
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
      ENDIF
      IF(WT1.GT.WT)THEN
        T1P1=0.82*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
588     IF(WT1.GT.WT)THEN
          GO TO 599
        ELSE
          T1P=T1P1
          T2P=T2P1
          WT=WT1
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'NO CONVERGENCE IN PEN4'
            GO TO 555
          ENDIF
          T1P1=0.9*T1P1
          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
          WT1=T1P1+T2P1
          GO TO 588
        ENDIF
      ELSE
577     T1P=T1P1
        T2P=T2P1
        WT=WT1
        T1P1=1.1*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
        IF(WT1.GT.WT)THEN
          GO TO 599
        ELSE
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'NO CONVERGENCE IN PEN4'
            GO TO 555
          ENDIF
          GO TO 577
        ENDIF
```

```
              ENDIF
      599     CONTINUE
              D=30.48*D
              T1P=30.48*T1P
              T2P=30.48*T2P
              IF(T1P/D.LE.0.4)VF=4100
              IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
              VF=VF+4000.
              IF(V.GT.VF)THEN
                WRITE(11,*)'OUTSIDE OF PEN4 LIMITS'
                GO TO 1100
              ENDIF
              T1=T1P
              T2=T2P
      555     CONTINUE
              WT=T1+T2
              R12=211.
              R22=211.+T2
              R11=211.+T2+10.
              R21=211.+T1+T2+10.
              VB=4.27*(R21**2.-R11**2.)
              VW=4.27*(R22**2.-R12**2.)
              WTCMC=RHO1*VB+RHO2*VW
      1100    RETURN
              END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 775 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 44 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 120 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 939 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | PEN4 |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | I*4 | NITSP | ** | I*4 | NP1 |
| ** | R*4 | R12 | ** | R*4 | R21 | ** | R*4 | R22 |
| AP-00000014@ | R*4 | RHO2 | AP-0000000C@ | R*4 | RHOP | 2-00000000 | R*4 | RP |
| AP-0000001C@ | R*4 | SY2 | AP-00000024@ | R*4 | T1 | 2-00000004 | R*4 | T1P |
| AP-00000028@ | R*4 | T2 | ** | R*4 | T2P | ** | R*4 | T2P1 |
| AP-00000004@ | R*4 | V | ** | R*4 | VB | 2-0000000C | R*4 | VF |

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SAIC

# IMPACT5V

IMPACT5V is a spacecraft protective systems design optimization code similar to IMPACT5. IMPACT5V differs from IMPACT5 in that the optimal design is weighted according to the chosen space debris velocity probability distribution. IMPACT5V employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the space debris velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5V is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution files for 500 Km altitude and 30 degree inclination (500KM30DEG.DAT) and 60 degree inclination (500KM60 DEG.DAT) follow. The file being used must be assigned to FOR012 before running IMPACT5V. Sample input (IMPACT5V.IN), output (IMPACT5V.OUT), and program listing (IMPACT5V.LIS) follow the velocity distribution files.

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SAIC

| | |
|---|---|
| 1 | 0.005 |
| 2 | 0.005 |
| 3 | 0.02 |
| 4 | 0.05 |
| 5 | 0.10 |
| 6 | 0.05 |
| 7 | 0.075 |
| 8 | 0.08 |
| 9 | 0.07 |
| 10 | 0.23 |
| 11 | 0.155 |
| 12 | 0.08 |
| 13 | 0.05 |
| 14 | 0.02 |
| 15 | 0.005 |
| 16 | 0.005 |

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SAIC

| | |
|---|---|
| 1 | 0.01 |
| 2 | 0.01 |
| 3 | 0.01 |
| 4 | 0.01 |
| 5 | 0.03 |
| 6 | 0.03 |
| 7 | 0.01 |
| 8 | 0.01 |
| 9 | 0.005 |
| 10 | 0.09 |
| 11 | 0.09 |
| 12 | 0.07 |
| 13 | 0.28 |
| 14 | 0.28 |
| 15 | 0.065 |
| 16 | 0.005 |

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```
5               !NUMBER OF CASES
1               !NYSMITH PREDICTOR
0.84            !PROJ. DIAMETER IN CM
10.             !BUMPER/WALL SEPARATION IN CM
2               !BOEING PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
7344000.        !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.        !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3               !MADDEN PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
2.81            !BUMPER/WALL DENSITY IN GM/CUBIC CM
4               !WILKINSON PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
5               !BURCH PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
```

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NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2498978 CM
WALL THICKNESS = 0.4648098 CM
MIN. WEIGHT = 0.7147076 CM
CMC MIN. WEIGHT = 3685.385 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

INSIDE OF PEN4 LIMITS
INSIDE OF PEN4 LIMITS
OUTPUT

BUMPER THICKNESS = 0.1605087 CM
WALL THICKNESS = 0.5884032 CM
MIN. WEIGHT = 0.7489119 CM
CMC MIN. WEIGHT = 3837.381 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3522651 CM
WALL THICKNESS = 0.3522651 CM
MIN. WEIGHT = 0.7045302 CM
CMC MIN. WEIGHT = 3657.869 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.1978996 CM
WALL THICKNESS = 0.1978996 CM
MIN. WEIGHT = 0.3957993 CM
CMC MIN. WEIGHT = 2053.512 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.1434212 CM
WALL THICKNESS = 0.6418241 CM
MIN. WEIGHT = 0.7852453 CM
CMC MIN. WEIGHT = 4017.877 KG

```
      DIMENSION XPV(16)
      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5V.IN',ACCESS='SEQUENTIAL')
      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5V.OUT',ACCESS='SEQUENTIAL')
      DO 24 I=1,16
         READ(12,*)IV,XPV(IV)
24    CONTINUE
      READ(10,*)NRUNS
      DO 10 I=1,NRUNS
        READ(10,*)NCODE
        IF(NCODE.EQ.1)GO TO 25
        IF(NCODE.EQ.2)GO TO 35
        IF(NCODE.EQ.3)GO TO 45
        IF(NCODE.EQ.4)GO TO 55
        IF(NCODE.EQ.5)GO TO 65
25      READ(10,*)D
        READ(10,*)H
        WRITE(11,*)'       NYSMITH'
        WRITE(11,*)
        WRITE(11,*)'       INPUT'
        WRITE(11,*)
        WRITE(11,*)'       PROJECTILE DIAMETER IN CM = ',D
        WRITE(11,*)'       BUMPER/WALL SEPARATION IN CM = ',H
        WRITE(11,*)
        T1T=0.0
        T2T=0.0
        DO 26 J=1,16
        V=FLOAT(J)
        CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
        T1T=T1T+T1*XPV(J)
        T2T=T2T+T2*XPV(J)
26      CONTINUE
        T1=T1T
        T2=T2T
        WT=T1+T2
        WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
        WTCMC=12.*WTCMC
        WRITE(11,*)'       OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'       BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'       WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'       MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'       CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
35      READ(10,*)D
        READ(10,*)RHOP
        READ(10,*)RHO1
        READ(10,*)RHO2
        READ(10,*)S
        READ(10,*)XL2
        READ(10,*)SY1
        READ(10,*)SY2
        READ(10,*)THETA
        READ(10,*)XN
```

```
          READ(10,*)E1
          WRITE(11,*)'        BOEING'
          WRITE(11,*)
          WRITE(11,*)'        INPUT'
          WRITE(11,*)
          WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
          WRITE(11,*)'        PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
          WRITE(11,*)'        BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
          WRITE(11,*)'        WALL DENSITY IN GM/CUBIC CM = ',RHO2
          WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
          WRITE(11,*)'        WALL MATERIAL CONSTANT = ',XL2
          WRITE(11,*)'        BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
          WRITE(11,*)'        WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
          WRITE(11,*)'        IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
          WRITE(11,*)'        NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                            ' BUMPER = ',XN
          WRITE(11,*)'        BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                       ' SEC = ',E1
          WRITE(11,*)
          T1T=0.0
          T2T=0.0
          DO 36 J=1,16
          V=FLOAT(J)
          CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &                XN,E1,T1,T2,WT,WTCMC)
          T1T=T1T+XPV(J)*T1
          T2T=T2T+XPV(J)*T2
   36     CONTINUE
          T1=T1T
          T2=T2T
          WT=T1+T2
          R12=211.
          R22=211.+T2
          R11=211.+T2+S
          R21=211.+T1+T2+S
          VB=4.27*(R21**2.-R11**2.)
          VW=4.27*(R22**2.-R12**2.)
          WTCMC=RHO1*VB+RHO2*VW
          WRITE(11,*)'        OUTPUT'
          WRITE(11,*)
          WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
   45     READ(10,*)D
          READ(10,*)RHOP
          READ(10,*)S
          READ(10,*)RHO
          WRITE(11,*)'        MADDEN'
          WRITE(11,*)
          WRITE(11,*)'        INPUT'
          WRITE(11,*)
          WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
```

```
              WRITE(11,*)'       PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
              WRITE(11,*)'       BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
              WRITE(11,*)'       BUMPER/WALL SEPARATION IN CM = ',S
              WRITE(11,*)
              T1T=0.0
              T2T=0.0
              DO 46 J=1,16
              V=FLOAT(J)
              CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
              T1T=T1T+T1*XPV(J)
              T2T=T2T+T2*XPV(J)
     46       CONTINUE
              T1=T1T
              T2=T2T
              WT=T1+T2
              R12=211.
              R22=211.+T2
              R11=211.+T2+S
              R21=211.+T1+T2+S
              VB=4.27*(R21**2.-R11**2.)
              VW=4.27*(R22**2.-R12**2.)
              WTCMC=RHO*(VB+VW)
              WRITE(11,*)'       OUTPUT'
              WRITE(11,*)
              WRITE(11,*)'       BUMPER THICKNESS = ',T1,'CM'
              WRITE(11,*)'       WALL THICKNESS = ',T2,'CM'
              WRITE(11,*)'       MIN. WEIGHT = ',WT,'CM'
              WRITE(11,*)'       CMC MIN. WEIGHT = ',WTCMC,'KG'
              WRITE(11,*)
              WRITE(11,*)
              WRITE(11,*)
              GO TO 10
     55       READ(10,*)D
              READ(10,*)RHOP
              READ(10,*)RHO1
              READ(10,*)RHO2
              READ(10,*)S
              READ(10,*)XL2
              WRITE(11,*)'       WILKINSON'
              WRITE(11,*)
              WRITE(11,*)'       INPUT'
              WRITE(11,*)
              WRITE(11,*)'       PROJECTILE DIAMETER IN CM = ',D
              WRITE(11,*)'       PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
              WRITE(11,*)'       BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
              WRITE(11,*)'       WALL DENSITY IN GM/CUBIC CM = ',RHO2
              WRITE(11,*)'       BUMPER/WALL SEPARATION IN CM = ',S
              WRITE(11,*)'       WALL MATERIAL CONSTANT = ',XL2
              WRITE(11,*)
              T1T=0.0
              T2T=0.0
              DO 56 J=1,16
              V=FLOAT(J)
              CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
          &                T1,T2,WT,WTCMC)
              T1T=T1T+T1*XPV(J)
              T2T=T2T+T2*XPV(J)
```

```
56      CONTINUE
        T1=T1T
        T2=T2T
        WT=T1+T2
        R12=211.
        R22=211.+T2
        R11=211.+T2+S
        R21=211.+T1+T2+S
        VB=4.27*(R21**2.-R11**2.)
        VW=4.27*(R22**2.-R12**2.)
        WTCMC=RHO1*VB+RHO2*VW
        WRITE(11,*)'       OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'       BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'       WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'       MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'       CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
65      READ(10,*)D
        READ(10,*)RHO1
        READ(10,*)S
        READ(10,*)THETA
        READ(10,*)XN
        READ(10,*)E1
*****  MODIFIED BURCH  *****
        WRITE(11,*)'       MODIFIED BURCH'
        WRITE(11,*)
        WRITE(11,*)'       INPUT'
        WRITE(11,*)
        WRITE(11,*)'       PROJECTILE DIAMETER IN CM = ',D
        WRITE(11,*)'       BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
        WRITE(11,*)'       BUMPER/WALL SEPARATION IN CM = ',S
        WRITE(11,*)'       IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
        WRITE(11,*)'       NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                    ' BUMPER = ',XN
        WRITE(11,*)'       BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                        ' SEC = ',E1
        WRITE(11,*)
        T1T=0.0
        T2T=0.0
        DO 66 J=1,16
        V=FLOAT(J)
        CALL BURCH(V,D,RHO1,S,THETA,
     &             XN,E1,T1,T2,WT,WTCMC)
        T1T=T1T+T1*XPV(J)
        T2T=T2T+T2*XPV(J)
66      CONTINUE
        T1=T1T
        T2=T2T
        WT=T1+T2
        R12=211.
        R22=211.+T2
        R11=211.+T2+S
        R21=211.+T1+T2+S
```

```
        VB=4.27*(R21**2.-R11**2.)
        VW=4.27*(R22**2.-R12**2.)
        WTCMC=RHO1*VB+2.81*VW
        WRITE(11,*)'         OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'         BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'         WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'         MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'         CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
10      CONTINUE
        STOP
        END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 4728 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 741 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 692 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 6161 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | IMPACT5V$MAIN |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| 2-0000004C | R*4 | D | 2-0000008C | R*4 | E1 | 2-00000050 | R*4 | H |
| 2-00000040 | I*4 | IV | ** | I*4 | J | 2-00000048 | I*4 | NCODE |
| ** | R*4 | R11 | ** | R*4 | R12 | ** | R*4 | R21 |
| 2-00000090 | R*4 | RHO | 2-0000006C | R*4 | RHO1 | 2-00000070 | R*4 | RHO2 |
| 2-00000074 | R*4 | S | 2-0000007C | R*4 | SY1 | 2-00000080 | R*4 | SY2 |
| ** | R*4 | T1T | 2-0000005C | R*4 | T2 | ** | R*4 | T2T |
| 2-00000054 | R*4 | V | ** | R*4 | VB | ** | R*4 | VW |
| 2-00000064 | R*4 | WTCMC | 2-00000078 | R*4 | XL2 | 2-00000088 | R*4 | XN |

```
          SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
          DMAX=0.24*H*V**-0.2
          IF(D.GT.DMAX)THEN
            WRITE(11,*)'    NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
            GO TO 16
          ENDIF
          T1=1.93*V**0.18*D**1.91/H**0.91
          T2=1.86*T1
16          CONTINUE
            RETURN
            END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 150 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 49 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 8 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 207 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | NYSMITH |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | DMAX | AP-0000000C@ | R*4 | H |
| AP-00000014@ | R*4 | T2 | AP-00000004@ | R*4 | V | AP-00000018@ | R*4 | WT |

LABELS

| Address | Label |
|---|---|
| 0-00000095 | 16 |

```
      SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &            XN,E1,T1,T2,WT,WTCMC)
***** PEN4  *****
      T1=0.16
      V=V*3280.
      D=D/30.48
      RP=D/2.0
      RHOP=RHOP*1.94
      RHO1=RHO1*1.94
      RHO2=RHO2*1.94
      NITSP=0
      NITSP=NITSP+1
      NP1=0
      T1P=T1/30.48
      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
      WT=T1P+T2P
      IF(NITSP.EQ.1)THEN
        T1P1=1.1*T1P
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
      ENDIF
      IF(WT1.GT.WT)THEN
        T1P1=0.82*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
590     IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          T1P=T1P1
          T2P=T2P1
          WT=WT1
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'    NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          T1P1=0.9*T1P1
          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
          WT1=T1P1+T2P1
          GO TO 590
        ENDIF
      ELSE
579     T1P=T1P1
        T2P=T2P1
        WT=WT1
        T1P1=1.1*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
        IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'    NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          GO TO 579
```

```
            ENDIF
          ENDIF
  601     CONTINUE
          D=30.48*D
          RHOP=RHOP/1.94
          RHO1=RHO1/1.94
          RHO2=RHO2/1.94
          T1P=30.48*T1P
          T2P=30.48*T2P
          IF(T1P/D.LE.0.4)VF=4100
          IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
          VF=VF+4000.
          IF(V.LE.VF)THEN
            WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
            T1=T1P
            T2=T2P
            GO TO 1102
          ENDIF
  557     CONTINUE
  *****  WILKINSON  *****
          V=V/3280.
          T1=0.604*D**2.*RHOP/S
          T1=T1*SQRT(V/(XL2*RHO1*RHO2))
          RATIO=D*RHOP/(T1*RHO1)
          IF(RATIO.GT.1.0)T2=T1
          IF(RATIO.LE.1.0)T2=T1/RATIO
  *****  MODIFIED BURCH  *****
          VB=V*3280.
          DB=D/2.54
          CM=SQRT(E1/RHO1)
          CM=CM/30.48
          SB=S/2.54
          IF(THETA.LE.0.001)GO TO 125
          CHI=TAN(THETA)-0.5
          F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
          F2=F2+(1.7-12.*T1B/D)*CHI
          F3=0.32*(T1B/D)**0.83
          F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
          T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
          T2F=T2F*(D/S)**0.71
          T2N=F3*(CM/V)**1.33*D/XN
          IF(T2N.GE.T2F)T2B=T2N
          IF(T2N.LT.T2F)T2B=T2F
          T2B=T2B*2.54
          IF(T2B.GT.T2)NREGION=3
          IF(T2B.GT.T2)T2=T2B
          GO TO 155
  125     CONTINUE
          T1B1=T1/2.54
          NITSB=0
          XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
          VDELTA=0.0
          DELTA3=0.52
  1099    DELTA2=2.33*(1.-1.57*DELTA3)
          DELTA1=1.33*(2.*DELTA3-1.)
          VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
          VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

```
          IF(VDELTA1.LT.VDELTA)THEN
            DELTA1=1.33*(2.*DELTA3-1.04)
            T1B=DELTA1*VDELTA
            T2B=VDELTA-T1B
            GO TO 499
          ENDIF
          VDELTA=VDELTA1
          DELTA3=DELTA3+0.02
          IF(DELTA3.GT.0.63)THEN
            T1B=DELTA1*VDELTA
            T2B=VDELTA-T1B
            GO TO 499
          ENDIF
          GO TO 1099
499       CONTINUE
*****    COMPARISON OF MODIFIED BURCH AND WILKINSON  *****
199       CONTINUE
          T10W=T1/2.54
          F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
          T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
          T2BT10W=T2BT10W/SB**0.71
          T2BT10W=T2BT10W*2.54
          RATIOB=(DB*RHOP)/(RHO1*T1B)
          T2WT10B=0.364*D**3.*RHOP*V/(XL2*RHO2*S**2.)
          IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
          IF(T2BT10W.GT.T2)T2=T2BT10W
          T2B=T2B*2.54
          IF(T2WT10B.GT.T2B)T2B=T2WT10B
          T1B=T1B*2.54
          IF(T1B+T2B.LT.T1+T2)THEN
            T1=T1B
            T2=T2B
          ENDIF
155       CONTINUE
1102        IF(T2.LE.0.01)THEN
              SIGMA=SY2/144.
              T2=3099.1/SIGMA
              ENDIF
156       RETURN
          END
```

```
      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
      F1=F1-4.18
      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
      RETURN
      END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 163 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 2 | $LOCAL | 4 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 167 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2B |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000010@ | R*4 | CM | AP-00000004@ | R*4 | DB | ** | R*4 | F1 |
| AP-00000008@ | R*4 | T1B | AP-00000014@ | R*4 | VB | AP-0000000C@ | R*4 | XN |

```
      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
      A=1.33*RHOP*(V*RP)**2.
      B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
      C=1.33*RHOP*RP**2.0
      D1=RP*RHO1/COS(THETA)
      XK1=1.67*(RHOP/(2.*SY2))**0.31
      XK1=XK1*(0.281*D*RHOP/RHO2)**0.33
      XK1=XK1*COS(THETA)
      C1P1=(A-B*T1P)/(C+D1*T1P)
      IF(C1P1.LE.0.001)THEN
        FT2P=0.0
        GO TO 999
      ENDIF
      FT2P=XK1*C1P1**0.31
  999 RETURN
      END
```



PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 222 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 2 | $LOCAL | 4 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 226 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2P |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| ** | R*4 | A | ** | R*4 | B | ** | R*4 | C |
| AP-00000020@ | R*4 | D | ** | R*4 | D1 | AP-00000018@ | R*4 | RHO1 |
| AP-00000004@ | R*4 | RHOP | AP-0000000C@ | R*4 | RP | AP-00000010@ | R*4 | SY1 |
| AP-00000028@ | R*4 | T1P | AP-00000014@ | R*4 | THETA | AP-00000008@ | R*4 | V |

LABELS

| Address | Label |
|---|---|
| 0-000000D9 | 999 |

```
      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
      V=V*1.E05
      T1=0.009*SQRT(V)*RHOP*D**2.0
      T1=T1/(S*RHO**1.5)
      T2=T1
      RETURN
      END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 69 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| | Total Space Allocated | 69 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | MADDEN |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | AP-00000014@ | R*4 | RHO | AP-0000000C@ | R*4 | RHOP |
| AP-00000018@ | R*4 | T1 | AP-0000001C@ | R*4 | T2 | AP-00000004@ | R*4 | V |
| AP-00000024@ | R*4 | WTCMC | | | | | | |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

```
      SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
     &                     T1,T2,WT,WTCMC)
      T1=0.604*D**2.*RHOP/S
      T1=T1*SQRT(V/(XL2*RHO1*RHO2))
      RATIO=D*RHOP/(T1*RHO1)
      IF(RATIO.GT.1.0)T2=T1
      IF(RATIO.LE.1.0)T2=T1/RATIO
      RETURN
      END
```



PROGRAM SECTIONS

| Name | Bytes | Attributes |
|---|---|---|
| 0 $CODE | 87 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| Total Space Allocated | 87 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | WILKINSON |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | RATIO | AP-00000010@ | R*4 | RHO1 |
| AP-0000000C@ | R*4 | RHOP | AP-00000018@ | R*4 | S | AP-00000020@ | R*4 | T1 |
| AP-00000004@ | R*4 | V | AP-00000028@ | R*4 | WT | AP-0000002C@ | R*4 | WTCMC |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

```
*****  MODIFIED BURCH  *****
      SUBROUTINE BURCH(V,D,RHO1,S,THETA,
     &            XN,E1,T1,T2,WT,WTCMC)
      VB=V*3280.
      DB=D/2.54
      CM=SQRT(E1/RHO1)
      CM=CM/30.48
      SB=S/2.54
      IF(THETA.LE.0.001)GO TO 425
      CHI=TAN(THETA)-0.5
      F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
      F2=F2+(1.7-12.*T1B/D)*CHI
      F3=0.32*(T1B/D)**0.83
      F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
      T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
      T2F=T2F*(D/S)**0.71
      T2N=F3*(CM/V)**1.33*D/XN
      IF(T2N.GE.T2F)T2B=T2N
      IF(T2N.LT.T2F)T2B=T2F
      T2B=T2B*2.54
      IF(T2B.GT.T2)NREGION=3
      IF(T2B.GT.T2)T2=T2B
      GO TO 499
425   CONTINUE
      NITSB=0
      XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
      VDELTA=0.0
      DELTA3=0.52
1099  DELTA2=2.33*(1.-1.57*DELTA3)
      DELTA1=1.33*(2.*DELTA3-1.)
      VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
      VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
      IF(VDELTA1.LT.VDELTA)THEN
        DELTA1=1.33*(2.*DELTA3-1.04)
        T1=DELTA1*VDELTA
        T2=VDELTA-T1
        GO TO 499
      ENDIF
      VDELTA=VDELTA1
      DELTA3=DELTA3+0.02
      IF(DELTA3.GT.0.63)THEN
        T1=DELTA1*VDELTA
        T2=VDELTA-T1
        GO TO 499
      ENDIF
      GO TO 1099
499   CONTINUE
      T1=T1*2.54
      T2=T2*2.54
      RETURN
      END
```

# IMPACT5VM

IMPACT5VM is a spacecraft protective systems design optimization code similar to IMPACT5V. IMPACT5VM differs from IMPACT5V in that the optimal design is weighted according to the chosen meteoroid velocity probability distribution. IMPACT5VM employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the meteoroid velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5VM is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution file for meteoroids, (METVEL.IN), follows. The file being used must be assigned to FOR012 before running IMPACT5VM. Sample input (IMPACT5VM.IN), output (IMPACT5VM.OUT), and program listing (IMPACT5VM.LIS) follow the velocity distribution file.

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| | |
|---|---|
| 9 | .045 |
| 10 | .045 |
| 11 | .045 |
| 12 | .045 |
| 13 | .25 |
| 14 | .25 |
| 15 | .25 |
| 16 | .26 |
| 17 | .26 |
| 18 | .26 |
| 19 | .14 |
| 20 | .14 |
| 21 | .14 |
| 22 | .10 |
| 23 | .10 |
| 24 | .10 |
| 25 | .06 |
| 26 | .06 |
| 27 | .06 |
| 28 | .05 |
| 29 | .05 |
| 30 | .05 |
| 31 | .025 |
| 32 | .025 |
| 33 | .025 |
| 34 | .015 |
| 35 | .015 |
| 36 | .015 |
| 37 | .012 |
| 38 | .012 |
| 39 | .012 |
| 40 | .011 |
| 41 | .011 |
| 42 | .011 |
| 43 | .009 |
| 44 | .009 |
| 45 | .009 |
| 46 | .0075 |
| 47 | .0075 |
| 48 | .0075 |
| 49 | .0075 |
| 50 | .0075 |
| 51 | .0075 |
| 52 | .0075 |
| 53 | .0075 |
| 54 | .0075 |
| 55 | .0075 |
| 56 | .0075 |
| 57 | .0075 |
| 58 | .0075 |
| 59 | .0075 |
| 60 | .0075 |
| 61 | .0075 |
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| 63 | .0075 |
| 64 | .0075 |
| 65 | .0075 |
| 66 | .0075 |
| 67 | .0075 |
| 68 | .0075 |

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|---|---|
| 69 | .0075 |
| 70 | .0075 |
| 71 | .0075 |
| 72 | .0075 |

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```
5               !NUMBER OF CASES
1               !NYSMITH PREDICTOR
0.84            !PROJ. DIAMETER IN CM
10.             !BUMPER/WALL SEPARATION IN CM
2               !BOEING PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
7344000.        !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.        !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3               !MADDEN PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
2.81            !BUMPER/WALL DENSITY IN GM/CUBIC CM
4               !WILKINSON PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !PROJ. DENSITY IN GM/CUBIC CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
2.81            !WALL DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.401           !WALL MATERIAL CONSTANT
5               !BURCH PREDICTOR
0.84            !PROJ. DIA. IN CM
2.81            !BUMPER DENSITY IN GM/CUBIC CM
10.             !BUMPER/WALL SEPARATION IN CM
0.              !IMPACT ANGLE FROM NORMAL
0.85            !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11        !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
```

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NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2964782 CM
WALL THICKNESS = 0.5514496 CM
MIN. WEIGHT = 0.8479279 CM
CMC MIN. WEIGHT = 4373.689 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.3065161 CM
WALL THICKNESS = 0.3286171 CM
MIN. WEIGHT = 0.6351332 CM
CMC MIN. WEIGHT = 3294.346 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.5543199 CM
WALL THICKNESS = 0.5543199 CM
MIN. WEIGHT = 1.108640 CM
CMC MIN. WEIGHT = 5761.344 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.3114124 CM
WALL THICKNESS = 0.3114124 CM
MIN. WEIGHT = 0.6228247 CM
CMC MIN. WEIGHT = 3233.087 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 4.5066189E-02CM
WALL THICKNESS = 9.7935580E-02CM
MIN. WEIGHT = 0.1430018 CM
CMC MIN. WEIGHT = 735.0610 KG

```
      DIMENSION XPV(100)
      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5VM.IN',ACCESS='SEQUENTIAL')
      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5VM.OUT',ACCESS='SEQUENTIAL')
      DO 24 I=1,64
         READ(12,*)IV,XPV(IV)
 24   CONTINUE
      READ(10,*)NRUNS
      DO 10 I=1,NRUNS
        READ(10,*)NCODE
        IF(NCODE.EQ.1)GO TO 25
        IF(NCODE.EQ.2)GO TO 35
        IF(NCODE.EQ.3)GO TO 45
        IF(NCODE.EQ.4)GO TO 55
        IF(NCODE.EQ.5)GO TO 65
 25     READ(10,*)D
        READ(10,*)H
        WRITE(11,*)'        NYSMITH'
        WRITE(11,*)
        WRITE(11,*)'        INPUT'
        WRITE(11,*)
        WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
        WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',H
        WRITE(11,*)
        T1T=0.0
        T2T=0.0
        DO 26 J=1,64
        K=J+8
        V=FLOAT(K)
        CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
        T1T=T1T+T1*XPV(K)
        T2T=T2T+T2*XPV(K)
 26     CONTINUE
        T1=T1T/3.1335
        T2=T2T/3.1335
        WT=T1+T2
        WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
        WTCMC=12.*WTCMC
        WRITE(11,*)'        OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
 35     READ(10,*)D
        READ(10,*)RHOP
        READ(10,*)RHO1
        READ(10,*)RHO2
        READ(10,*)S
        READ(10,*)XL2
        READ(10,*)SY1
        READ(10,*)SY2
        READ(10,*)THETA
```

```
          READ(10,*)XN
          READ(10,*)E1
          WRITE(11,*)'        BOEING'
          WRITE(11,*)
          WRITE(11,*)'        INPUT'
          WRITE(11,*)
          WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
          WRITE(11,*)'        PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
          WRITE(11,*)'        BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
          WRITE(11,*)'        WALL DENSITY IN GM/CUBIC CM = ',RHO2
          WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
          WRITE(11,*)'        WALL MATERIAL CONSTANT = ',XL2
          WRITE(11,*)'        BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
          WRITE(11,*)'        WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
          WRITE(11,*)'        IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
          WRITE(11,*)'        NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                                ' BUMPER = ',XN
          WRITE(11,*)'        BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                       ' SEC = ',E1
          WRITE(11,*)
          T1T=0.0
          T2T=0.0
          DO 36 J=1,64
          K=J+8
          V=FLOAT(K)
          CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &                XN,E1,T1,T2,WT,WTCMC)
          T1T=T1T+XPV(K)*T1
          T2T=T2T+XPV(K)*T2
   36     CONTINUE
          T1=T1T/3.1335
          T2=T2T/3.1335
          WT=T1+T2
          R12=211.
          R22=211.+T2
          R11=211.+T2+S
          R21=211.+T1+T2+S
          VB=4.27*(R21**2.-R11**2.)
          VW=4.27*(R22**2.-R12**2.)
          WTCMC=RHO1*VB+RHO2*VW
          WRITE(11,*)'        OUTPUT'
          WRITE(11,*)
          WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
          WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
          WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
          WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
          WRITE(11,*)
          WRITE(11,*)
          WRITE(11,*)
          GO TO 10
   45     READ(10,*)D
          READ(10,*)RHOP
          READ(10,*)S
          READ(10,*)RHO
          WRITE(11,*)'        MADDEN'
          WRITE(11,*)
          WRITE(11,*)'        INPUT'
```

```
      WRITE(11,*)
      WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
      WRITE(11,*)'        PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
      WRITE(11,*)'        BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
      WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
      WRITE(11,*)
      T1T=0.0
      T2T=0.0
      DO 46 J=1,64
      K=J+8
      V=FLOAT(K)
      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
      T1T=T1T+T1*XPV(K)
      T2T=T2T+T2*XPV(K)
46    CONTINUE
      T1=T1T/3.1335
      T2=T2T/3.1335
      WT=T1+T2
      R12=211.
      R22=211.+T2
      R11=211.+T2+S
      R21=211.+T1+T2+S
      VB=4.27*(R21**2.-R11**2.)
      VW=4.27*(R22**2.-R12**2.)
      WTCMC=RHO*(VB+VW)
      WRITE(11,*)'        OUTPUT'
      WRITE(11,*)
      WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
      WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
      WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
      WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
      WRITE(11,*)
      WRITE(11,*)
      WRITE(11,*)
      GO TO 10
55    READ(10,*)D
      READ(10,*)RHOP
      READ(10,*)RHO1
      READ(10,*)RHO2
      READ(10,*)S
      READ(10,*)XL2
      WRITE(11,*)'        WILKINSON'
      WRITE(11,*)
      WRITE(11,*)'        INPUT'
      WRITE(11,*)
      WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
      WRITE(11,*)'        PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
      WRITE(11,*)'        BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
      WRITE(11,*)'        WALL DENSITY IN GM/CUBIC CM = ',RHO2
      WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
      WRITE(11,*)'        WALL MATERIAL CONSTANT = ',XL2
      WRITE(11,*)
      T1T=0.0
      T2T=0.0
      DO 56 J=1,64
      K=J+8
      V=FLOAT(K)
```

```
              CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
     &                   T1,T2,WT,WTCMC)
              T1T=T1T+T1*XPV(K)
              T2T=T2T+T2*XPV(K)
   56         CONTINUE
              T1=T1T/3.1335
              T2=T2T/3.1335
              WT=T1+T2
              R12=211.
              R22=211.+T2
              R11=211.+T2+S
              R21=211.+T1+T2+S
              VB=4.27*(R21**2.-R11**2.)
              VW=4.27*(R22**2.-R12**2.)
              WTCMC=RHO1*VB+RHO2*VW
              WRITE(11,*)'        OUTPUT'
              WRITE(11,*)
              WRITE(11,*)'        BUMPER THICKNESS = ',T1,'CM'
              WRITE(11,*)'        WALL THICKNESS = ',T2,'CM'
              WRITE(11,*)'        MIN. WEIGHT = ',WT,'CM'
              WRITE(11,*)'        CMC MIN. WEIGHT = ',WTCMC,'KG'
              WRITE(11,*)
              WRITE(11,*)
              WRITE(11,*)
              GO TO 10
   65         READ(10,*)D
              READ(10,*)RHO1
              READ(10,*)S
              READ(10,*)THETA
              READ(10,*)XN
              READ(10,*)E1
 *****      MODIFIED BURCH   *****
              WRITE(11,*)'        MODIFIED BURCH'
              WRITE(11,*)
              WRITE(11,*)'        INPUT'
              WRITE(11,*)
              WRITE(11,*)'        PROJECTILE DIAMETER IN CM = ',D
              WRITE(11,*)'        BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
              WRITE(11,*)'        BUMPER/WALL SEPARATION IN CM = ',S
              WRITE(11,*)'        IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
              WRITE(11,*)'        NUMBER OF PLATES TO PENETRATE AFTER FIRST',
     &                          ' BUMPER = ',XN
              WRITE(11,*)'        BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
     &                              ' SEC = ',E1
              WRITE(11,*)
              T1T=0.0
              T2T=0.0
              DO 66 J=1,64
              K=J+8
              V=FLOAT(K)
              CALL BURCH(V,D,RHO1,S,THETA,
     &                   XN,E1,T1,T2,WT,WTCMC)
              T1T=T1T+T1*XPV(K)
              T2T=T2T+T2*XPV(K)
   66         CONTINUE
              T1=T1T/3.1335
              T2=T2T/3.1335
```

```
        WT=T1+T2
        R12=211.
        R22=211.+T2
        R11=211.+T2+S
        R21=211.+T1+T2+S
        VB=4.27*(R21**2.-R11**2.)
        VW=4.27*(R22**2.-R12**2.)
        WTCMC=RHO1*VB+2.81*VW
        WRITE(11,*)'      OUTPUT'
        WRITE(11,*)
        WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
        WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
        WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
        WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
        WRITE(11,*)
        WRITE(11,*)
        WRITE(11,*)
        GO TO 10
10      CONTINUE
        STOP
        END
```

## ›ROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 4826 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 743 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 1028 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 6597 | |

## :NTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | IMPACT5VM$MAIN |

## /ARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| 2-0000019C | R*4 | D | 2-000001DC | R*4 | E1 | 2-000001A0 | R*4 | H |
| 2-00000190 | I*4 | IV | ** | I*4 | J | ** | I*4 | K |
| 2-00000194 | I*4 | NRUNS | ** | R*4 | R11 | ** | R*4 | R12 |
| ** | R*4 | R22 | 2-000001E0 | R*4 | RHO | 2-000001BC | R*4 | RHO1 |
| 2-000001B8 | R*4 | RHOP | 2-000001C4 | R*4 | S | 2-000001CC | R*4 | SY1 |
| 2-000001A8 | R*4 | T1 | ** | R*4 | T1T | 2-000001AC | R*4 | T2 |
| 2-000001D4 | R*4 | THETA | 2-000001A4 | R*4 | V | ** | R*4 | VB |
| 2-000001B0 | R*4 | WT | 2-000001B4 | R*4 | WTCMC | 2-000001C8 | R*4 | XL2 |

```
      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
      DMAX=0.24*H*V**-0.2
      IF(D.GT.DMAX)THEN
        WRITE(11,*)'    NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
        GO TO 16
      ENDIF
      T1=1.93*V**0.18*D**1.91/H**0.91
      T2=1.86*T1
16       CONTINUE
         RETURN
         END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 150 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 1 | $PDATA | 49 | PIC CON REL LCL SHR NOEXE RD NOWRT LONG |
| 2 | $LOCAL | 8 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 207 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | NYSMITH |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | DMAX | AP-0000000C@ | R*4 | H |
| AP-00000014@ | R*4 | T2 | AP-00000004@ | R*4 | V | AP-00000018@ | R*4 | WT |

LABELS

| Address | Label |
|---|---|
| 0-00000095 | 16 |

```
      SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
     &            XN,E1,T1,T2,WT,WTCMC)
*****  PEN4  *****
      T1=0.16
      V=V*3280.
      D=D/30.48
      RP=D/2.0
      RHOP=RHOP*1.94
      RHO1=RHO1*1.94
      RHO2=RHO2*1.94
      NITSP=0
      NITSP=NITSP+1
      NP1=0
      T1P=T1/30.48
      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
      WT=T1P+T2P
      IF(NITSP.EQ.1)THEN
        T1P1=1.1*T1P
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
      ENDIF
      IF(WT1.GT.WT)THEN
        T1P1=0.82*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
590     IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          T1P=T1P1
          T2P=T2P1
          WT=WT1
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'    NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          T1P1=0.9*T1P1
          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
          WT1=T1P1+T2P1
          GO TO 590
        ENDIF
      ELSE
579     T1P=T1P1
        T2P=T2P1
        WT=WT1
        T1P1=1.1*T1P1
        T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
        WT1=T1P1+T2P1
        IF(WT1.GT.WT)THEN
          GO TO 601
        ELSE
          NP1=NP1+1
          IF(NP1.EQ.100)THEN
            WRITE(11,*)'    NO CONVERGENCE IN PEN4'
            GO TO 557
          ENDIF
          GO TO 579
```

```
                ENDIF
              ENDIF
        601   CONTINUE
              D=30.48*D
              RHOP=RHOP/1.94
              RHO1=RHO1/1.94
              RHO2=RHO2/1.94
              T1P=30.48*T1P
              T2P=30.48*T2P
              IF(T1P/D.LE.0.4)VF=4100
              IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
              VF=VF+4000.
              IF(V.LE.VF)THEN
                WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
                T1=T1P
                T2=T2P
                GO TO 1102
              ENDIF
        557   CONTINUE
        *****  WILKINSON  *****
              V=V/3280.
              T1=0.604*D**2.*RHOP/S
              T1=T1*SQRT(V/(XL2*RHO1*RHO2))
              RATIO=D*RHOP/(T1*RHO1)
              IF(RATIO.GT.1.0)T2=T1
              IF(RATIO.LE.1.0)T2=T1/RATIO
        *****  MODIFIED BURCH  *****
              VB=V*3280.
              DB=D/2.54
              CM=SQRT(E1/RHO1)
              CM=CM/30.48
              SB=S/2.54
              IF(THETA.LE.0.001)GO TO 125
              CHI=TAN(THETA)-0.5
              F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
              F2=F2+(1.7-12.*T1B/D)*CHI
              F3=0.32*(T1B/D)**0.83
              F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
              T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
              T2F=T2F*(D/S)**0.71
              T2N=F3*(CM/V)**1.33*D/XN
              IF(T2N.GE.T2F)T2B=T2N
              IF(T2N.LT.T2F)T2B=T2F
              T2B=T2B*2.54
              IF(T2B.GT.T2)NREGION=3
              IF(T2B.GT.T2)T2=T2B
              GO TO 155
        125   CONTINUE
              T1B1=T1/2.54
              NITSB=0
              XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
              VDELTA=0.0
              DELTA3=0.52
       1099   DELTA2=2.33*(1.-1.57*DELTA3)
              DELTA1=1.33*(2.*DELTA3-1.)
              VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
              VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

```
          IF(VDELTA1.LT.VDELTA)THEN
            DELTA1=1.33*(2.*DELTA3-1.04)
            T1B=DELTA1*VDELTA
            T2B=VDELTA-T1B
            GO TO 499
          ENDIF
          VDELTA=VDELTA1
          DELTA3=DELTA3+0.02
          IF(DELTA3.GT.0.63)THEN
            T1B=DELTA1*VDELTA
            T2B=VDELTA-T1B
            GO TO 499
          ENDIF
          GO TO 1099
  499     CONTINUE
  *****  COMPARISON OF MODIFIED BURCH AND WILKINSON  *****
  199     CONTINUE
          T10W=T1/2.54
          F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
          T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
          T2BT10W=T2BT10W/SB**0.71
          T2BT10W=T2BT10W*2.54
          RATIOB=(DB*RHOP)/(RHO1*T1B)
          T2WT10B=0.364*D**3.*RHOP*V/(XL2*RHO2*S**2.)
          IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
          IF(T2BT10W.GT.T2)T2=T2BT10W
          T2B=T2B*2.54
          IF(T2WT10B.GT.T2B)T2B=T2WT10B
          T1B=T1B*2.54
          IF(T1B+T2B.LT.T1+T2)THEN
            T1=T1B
            T2=T2B
          ENDIF
  155     CONTINUE
  1102      IF(T2.LE.0.01)THEN
              SIGMA=SY2/144.
              T2=3099.1/SIGMA
              ENDIF
  156     RETURN
          END
```

```
      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
      F1=F1-4.18
      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
      RETURN
      END
```

## PROGRAM SECTIONS

| Name | Bytes | Attributes |
|---|---|---|
| 0 $CODE | 163 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 2 $LOCAL | 4 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| Total Space Allocated | 167 | |

## ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2B |

## VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000010@ | R*4 | CM | AP-00000004@ | R*4 | DB | ** | R*4 | F1 |
| AP-00000008@ | R*4 | T1B | AP-00000014@ | R*4 | VB | AP-0000000C@ | R*4 | XN |

```
              FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
              A=1.33*RHOP*(V*RP)**2.
              B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
              C=1.33*RHOP*RP**2.0
              D1=RP*RHO1/COS(THETA)
              XK1=1.67*(RHOP/(2.*SY2))**0.31
              XK1=XK1*(0.281*D*RHOP/RHO2)**0.33
              XK1=XK1*COS(THETA)
              C1P1=(A-B*T1P)/(C+D1*T1P)
              IF(C1P1.LE.0.001)THEN
                FT2P=0.0
                GO TO 999
              ENDIF
              FT2P=XK1*C1P1**0.31
       999    RETURN
              END
```

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ROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 222 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| 2 | $LOCAL | 4 | PIC CON REL LCL NOSHR NOEXE RD WRT LONG |
| | Total Space Allocated | 226 | |

NTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | R*4 | FT2P |

ARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| ** | R*4 | A | ** | R*4 | B | ** | R*4 | C |
| AP-00000020@ | R*4 | D | ** | R*4 | D1 | AP-00000018@ | R*4 | RHO1 |
| AP-00000004@ | R*4 | RHOP | AP-0000000C@ | R*4 | RP | AP-00000010@ | R*4 | SY1 |
| AP-00000028@ | R*4 | T1P | AP-00000014@ | R*4 | THETA | AP-00000008@ | R*4 | V |

ABELS

| Address | Label |
|---|---|
| 0-000000D9 | 999 |

```
      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
      V=V*1.E05
      T1=0.009*SQRT(V)*RHOP*D**2.0
      T1=T1/(S*RHO**1.5)
      T2=T1
      RETURN
      END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 69 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| | Total Space Allocated | 69 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | MADDEN |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | AP-00000014@ | R*4 | RHO | AP-0000000C@ | R*4 | RHOP |
| AP-00000018@ | R*4 | T1 | AP-0000001C@ | R*4 | T2 | AP-00000004@ | R*4 | V |
| AP-00000024@ | R*4 | WTCMC | | | | | | |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

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```
      SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
     &                     T1,T2,WT,WTCMC)
      T1=0.604*D**2.*RHOP/S
      T1=T1*SQRT(V/(XL2*RHO1*RHO2))
      RATIO=D*RHOP/(T1*RHO1)
      IF(RATIO.GT.1.0)T2=T1
      IF(RATIO.LE.1.0)T2=T1/RATIO
      RETURN
      END
```

PROGRAM SECTIONS

| | Name | Bytes | Attributes |
|---|---|---|---|
| 0 | $CODE | 87 | PIC CON REL LCL SHR EXE RD NOWRT LONG |
| | Total Space Allocated | 87 | |

ENTRY POINTS

| Address | Type | Name |
|---|---|---|
| 0-00000000 | | WILKINSON |

VARIABLES

| Address | Type | Name | Address | Type | Name | Address | Type | Name |
|---|---|---|---|---|---|---|---|---|
| AP-00000008@ | R*4 | D | ** | R*4 | RATIO | AP-00000010@ | R*4 | RHO1 |
| AP-0000000C@ | R*4 | RHOP | AP-00000018@ | R*4 | S | AP-00000020@ | R*4 | T1 |
| AP-00000004@ | R*4 | V | AP-00000028@ | R*4 | WT | AP-0000002C@ | R*4 | WTCMC |

FUNCTIONS AND SUBROUTINES REFERENCED

| Type | Name |
|---|---|
| R*4 | MTH$SQRT |

```
*****  MODIFIED BURCH  *****
       SUBROUTINE BURCH(V,D,RHO1,S,THETA,
     &              XN,E1,T1,T2,WT,WTCMC)
       VB=V*3280.
       DB=D/2.54
       CM=SQRT(E1/RHO1)
       CM=CM/30.48
       SB=S/2.54
       IF(THETA.LE.0.001)GO TO 425
       CHI=TAN(THETA)-0.5
       F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
       F2=F2+(1.7-12.*T1B/D)*CHI
       F3=0.32*(T1B/D)**0.83
       F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
       T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
       T2F=T2F*(D/S)**0.71
       T2N=F3*(CM/V)**1.33*D/XN
       IF(T2N.GE.T2F)T2B=T2N
       IF(T2N.LT.T2F)T2B=T2F
       T2B=T2B*2.54
       IF(T2B.GT.T2)NREGION=3
       IF(T2B.GT.T2)T2=T2B
       GO TO 499
425    CONTINUE
       NITSB=0
       XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
       VDELTA=0.0
       DELTA3=0.52
1099   DELTA2=2.33*(1.-1.57*DELTA3)
       DELTA1=1.33*(2.*DELTA3-1.)
       VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
       VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
       IF(VDELTA1.LT.VDELTA)THEN
         DELTA1=1.33*(2.*DELTA3-1.04)
         T1=DELTA1*VDELTA
         T2=VDELTA-T1
         GO TO 499
       ENDIF
       VDELTA=VDELTA1
       DELTA3=DELTA3+0.02
       IF(DELTA3.GT.0.63)THEN
         T1=DELTA1*VDELTA
         T2=VDELTA-T1
         GO TO 499
       ENDIF
       GO TO 1099
499    CONTINUE
       T1=T1*2.54
       T2=T2*2.54
       RETURN
       END
```