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

FINAL REPORT (NAS8-37378)

Robert A. Mog
D. Marvin Price

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

BM15-8/11
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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
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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## 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
TERMINOLOGY (CONTINUED)

- A MATHEMATICAL RELATIONSHIP THAT MAY BE WRITTEN EXPLICITLY

FUNCTIONAL

- A MODEL, EITHER FUNCTIONAL OR NON-FUNCTIONAL, WHICH DESCRIBES THE IMPACT PHYSICS (E.G., NYHOLM, WILKINSON, BURCH, MODIFIED BURCH, PEN4, BOEING, MADDEN, RICHARDSON)

PREDICTOR

- A PREDICTOR WHOSE INDEPENDENT VARIABLES HAVE EXPONENTS THAT ARE NOT ALL EQUAL TO UNITY

NONLINEAR

- IN AN OPTIMIZATION TECHNIQUE, THE NUMBER OF VARIABLES THAT MUST BE SOLVED FOR MINUS THE NUMBER OF INDEPENDENT EQUATIONS AVAILABLE

DEGREE-OF-DIFFICULTY

- AN EQUATION OR INEQUALITY WHICH LIMITS THE USAGE OF A PREDICTOR

CONSTRAINT

- A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND WHOSE INDEPENDENT VARIABLES ARE POSITIVE-VALUED

POSTNOMIAL
PARAMETER SPACE

IDEALIZED SCENARIO

OBJECTIVE FUNCTION

INFLECTION

PIECEWISE CONTINUOUS

MONOTONIC

THE TOTAL NUMBER OF POSSIBLE INDEPENDENT VARIABLES ASSOCIATED WITH A PREDICTOR

AN IMPACT SCENARIO SIMILAR TO A TEST SETUP AND CHARACTERIZED BY FLAT PLATES MODELING THE BUMPER AND WALL AND NO SUPPORT STRUCTURE

THE EQUATION OR FUNCTION WHICH CHARACTERIZES THE OPTIMIZATION GOAL OF THE SYSTEM DESIGNER

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

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

STRICTLY INCREASING, DECREASING, OR CONSTANT
WHAT YOU WILL SEE IN SECTION I

- PROTECTIVE SYSTEMS DESIGN OPTIMIZATION PROBLEM FORMULATION
- DISCUSSION OF SPECIFIC OPTIMIZATION TECHNIQUE ATTRIBUTES
- EXAMPLE APPLICATION
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.
WHY THIS DESIGN OPTIMIZATION IS IMPORTANT

- METEOROID AND SPACE DEBRIS ENVIRONMENTS
- SAFETY IS A HIGH PRIORITY
- DESIGN FEASIBILITY IS AT STAKE
- THE ENVIRONMENT IS NOT STATIC
- IMPACT SCIENCE IS YOUNG
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

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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
IDEALIZED SPACECRAFT IMPACT SCENARIO

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

IDEALIZED SPACECRAFT IMPACT SCENARIO

\[ M_p \rho_p \rightarrow v_p \]

\[ \begin{array}{cccc}
\rho_1 & \rho_2 & \rho_{n-1} & \rho_n \\
S_{12} & S_{2} & S_{n-1,n} & \\
t_1 & t_2 & t_{n-1} & t_n \\
\end{array} \]

**BUMPERS**

**WALL**

\[ M_p = \text{mass of projectile} \]
\[ \rho_p = \text{density of projectile} \]
\[ v_p = \text{velocity of projectile} \]
\[ t_i = \text{bumper thickness, } i=1, 2, \ldots, n-1 \]  
\[ t_n = \text{wall thickness} \]  
\[ \rho_i = \text{bumper density, } i=1, 2, \ldots, n-1 \]  
\[ \rho_n = \text{wall density} \]  
\[ S_{i, i+1} = \text{distance between bumper } i \text{ and bumper } i+1. \]

**“WEIGHT” FUNCTION:**

\[ W_T = \sum_{i=1}^{n} \rho_i t_i \]

for constant normal plate areas.
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.
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 OPTIMI-
ZATION 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 COEF-
FICIENTS. ANOTHER ADVANTAGE TO GEOMETRIC PROGRAMMING IS THE
METHOD'S ABILITY TO ACCOMMODATE MANY TYPES OF INEQUALITY
CONSTRAINTS.
ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES (Continued)

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

\[ \frac{t_2}{d} = \frac{5.08 V^{0.278}}{\left(\frac{t_1}{d}\right)^{0.528} \left(\frac{h}{d}\right)^{1.39}}, \text{ valid for } \]

\[ \frac{t_1}{d} \leq 0.5 \text{ and } \frac{t_2}{d} \leq 1.0, \]

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

h=10 cm
v=10 km/sec

MINIMUM "WEIGHT" (cm)

PROJECTILE DIAMETER (d) (cm)

COMPUTER SOLUTION

ANALYTIC SOLUTION

NO SOLUTION

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

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 INFECTION POINTS OCCURRING AT A DIAMETER OF 1 CM.
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SECTION II

NYSMITH PREDICTOR
APPLIED TO
IDEALIZED SCENARIO
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

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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**

<table>
<thead>
<tr>
<th>DESIGN ASSUMPTIONS</th>
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<tbody>
<tr>
<td>$P_o = 0.97$ (PROBABILITY OF NO PENETRATION)</td>
</tr>
<tr>
<td>$T = 10$ YRS (MISSION DURATION)</td>
</tr>
<tr>
<td>$A_d = 574$ m$^2$ (DEBRIS AREA)</td>
</tr>
<tr>
<td>$A_m = 403$ m$^2$ (METEOROID AREA)</td>
</tr>
<tr>
<td>$Alt = 500$ km (AVERAGE ALTITUDE)</td>
</tr>
<tr>
<td>$V_m = 20$ km/sec (AVERAGE METEOROID VELOCITY)</td>
</tr>
<tr>
<td>$V_D = 10$ km/sec (AVERAGE DEBRIS VELOCITY)</td>
</tr>
<tr>
<td>$\rho_m = 0.5$ gm/cm$^3$ (METEOROID DENSITY)</td>
</tr>
<tr>
<td>$\rho_D = 2.81$ gm/cm$^3$ (DEBRIS DENSITY)</td>
</tr>
<tr>
<td>$h = 10$ cm (BUMPER/WALL SEPARATION)</td>
</tr>
</tbody>
</table>

**OPTIMAL DESIGN (BALLISTIC LIMIT)**

<table>
<thead>
<tr>
<th>BUMPER</th>
<th>WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{10} = 0.26$ cm (0.10 IN)</td>
<td></td>
</tr>
<tr>
<td>$l_{20} = 0.48$ cm (0.19 IN)</td>
<td></td>
</tr>
</tbody>
</table>

NYSMITH EQUATION
IDEALIZED SCENARIO
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.

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DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

IDEALIZED SCENARIO CRITICAL EVALUATION TASK FORCE  
CORE MODULE CONFIGURATION

MINIMUM "WEIGHT" (t × 10 + t² 0) (cm)

TOTAL CORE MODULE SYSTEM AREA (m²)

EQIIVALENT DEBRIS AREA FOR CURRENT DESIGN ≈ 330M²

- Po = 0.97
- T = 10 yrs
- Alt = 500 km
- Vm = 20 km/sec
- VD = 10 km/sec
- ρm = 0.5 gm/cm³
- ρD = 2.81 gm/cm³
- h = 10 cm

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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 ILLUSTRATED. ALTHOUGH THIS REDUCTION IN $P_0$ REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.
DEBRIS ENVIRONMENT DRIVES DESPITE \( P_0 \) REDUCTION

- \( P_0 = 0.95 \)
- \( T = 10 \) YRS
- \( \text{Alt} = 500 \) km
- \( V_m = 20 \) km/sec
- \( V_D = 10 \) km/sec
- \( \rho = 0.5 \) gms/cm\(^3\)
- \( h = 2.81 \) gms/cm\(^3\)
- \( h = 10 \) cm

IDEALIZED SCENARIO
CRITICAL EVALUATION TASK FORCE
CORE MODULE CONFIGURATION

MINIMUM "WEIGHT" \( t + \frac{t}{20} \) (cm)

TOTAL CORE MODULE SYSTEM AREA (m\(^2\))

DEBRIS
METEOROID

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

\[ P_0 = 0.99 \]

- $T = 10$ 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

---

**MINIMUM "WEIGHT" ($t_{10} + t_{20}$) (cm)**

- DEBRIS
- $d \geq 1.0$ cm

**METEOROID**

---

**TOTAL CORE MODULE SYSTEM AREA (m$^2$)**

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COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

![Graph showing the relationship between computer solution strip width and projectile velocity for various bumper/wall separations.](image-url)
GP METHOD CONFIRMS THE MINIMUM WEIGHT

GP METHOD CONFIRMS THE MINIMUM WEIGHT

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

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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.
OPTIMAL THICKNESSES VARY LINEARLY WITH MINIMUM "WEIGHT"

- NYSMITH EQUATION

WALL ($t_{20}$)

BUMPER ($t_{10}$)

MINIMUM "WEIGHT" ($t_{10} + t_{20}$) (CM)
OPTIMAL WALL THICKNESS VARIES LINEARLY WITH OPTIMAL BUMPER THICKNESS

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.

BM18-9/1

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OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

- V = 10 km/sec
- Nysmith Equation
- Idealized Scenario

THIRD INEQUALITY CONSTRAINT OF NYSMITH

CORE MODULE VOLUME CONSTRAINT

Equivalent Separation for Current Design = 17 cm

<table>
<thead>
<tr>
<th>d(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
</tr>
<tr>
<td>0.84</td>
</tr>
<tr>
<td>0.67</td>
</tr>
</tbody>
</table>

BUMPER/WALL SEPARATION (h) (cm)
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

- V = 10 Km/sec
- Nymphsmith Equation
- h = Bumper/Wall Separation

Diagram:
- Equivalent Projectile Diameter for Current Design = 0.93 cm
- Minimum Weight (10 + 1.20) (cm)
- h = 20 cm
- h = 15 cm
- h = 10 cm
- h = 5 cm
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.
OPTIMAL DESIGN IS SENSITIVE TO THREAT

- $V = 10$ Km/sec
- Nysmith Equation
- $h = \text{Bumper/Wall Separation}$

OPTIMAL BUMPER THICKNESS ($t_0$) (cm)

PROJECTILE DIAMETER ($d$) (cm)
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.
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.
OPTIMAL DESIGN IS SENSITIVE TO THREAT

- $V = 16\text{ Km/sec}$
- Nysmith Equation
- Idealized Scenario

OPTIMAL BUMPER THICKNESS ($t_0$) (cm)

PROJECTILE DIAMETER ($d$) (cm)
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.
GP METHOD PROVIDES THE MINIMUM BUMPER/WALL SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS.
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

- $h = 5 \text{ cm}$
- NYSMITH EQUATION
- IDEALIZED SCENARIO

MINIMUM "WEIGHT" ($t \cdot 10 + t \cdot 20$) (cm)

PROJECTILE VELOCITY (km/sec)

$\text{d} = 1.00 \text{ cm}$
$\text{d} = 0.84 \text{ cm}$
$\text{d} = 0.67 \text{ cm}$

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MC 12 OT 5/87 RWL

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

\[ h = 10 \text{ cm} \]

\[ \text{MYSMITH EQUATION IMPLIES IDEALIZED SCENARIO} \]

\[ \text{EQUIVALENT PROJECTILE VELOCITY FOR CURRENT DESIGN: 2.5 km/sec} \]

PROJETILE VELOCITY (km/sec)

MINIMUM WEIGHT \((\frac{1}{10} + \frac{1}{20}) \text{ (cm)}\)

Graph showing the relationship between projectile velocity and minimum weight.
OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- $h = 15$ cm
- NYSMITH EQUATION
- IDEALIZED SCENARIO

UNCLASSIFIED
MC 14 OT 5/87 RWL
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.
OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

- $V = 10\text{Km/sec}$
- $T = 10\text{ years}$
- $h = 10\text{ cm}$
- Nysmith Equation
- Idealized Scenario

EQUIVALENT MISSION RISK FOR CURRENT DESIGN $\sim 5.8\%$ ($P_0 \sim 0.942$)
OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P₀ ABOVE 0.97

- V = 10 Km/sec
- T = 10 years
- h = 5 cm
- Nysmith Equation
- Idealized Scenario

MINIMUM "WEIGHT" (t10+t20) (cm)

ACCEPTABLE MISSION RISK (1-P₀)

Area (m²)
- 688
- 574
- 459

SAIC
Acceptable Mission Risk (1-p, 0)

MINIMUM "WEIGHT" (t, 10^4 t 20) (cm)

Area (m^2)

4.9
5.74
6.88

Idealized Scenario

Nyestib Equation

h = 15 cm
T = 10 years
V = 10 km/sec

FOR P > 0.97

Optimal design is highly sensitive to Mission Risk
OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT P_0s, 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.

- $P_0 = 0.97$
- $h = 10\ cm$
- $v = 10\ \text{km/sec}$

- Nysmith Equation
- Idealized Scenario

Minimum "weight" ($t \cdot 10^t + 20\) (cm)

Equivalent mission duration for current design = 51/2 yrs
Optimal design is highly sensitive to mission duration in 10-30 year region.

- \( P_0 = 0.95 \)
- \( h = 10 \text{ cm} \)
- \( V = 10 \text{ km/sec} \)

Nysmith Equation

Idealized Scenario

\[ A = 688 \text{ m}^2 \]
\[ A = 574 \text{ m}^2 \]
\[ A = 459 \text{ m}^2 \]
SECTION III

NYSMITH PREDICTOR
APPLIED TO
CORE MODULE CONFIGURATION
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
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

534.14
1356.16
470.15
1941.9
166.00
4268.4
84.00
2133.6
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 NEGLI-
GIBLE PROVIDED THE BUMPER AND WALL THICKNESSES ARE SMALL IN COM-
PARISON TO THE MODULE RADIUS. THE MATHEMATICS BEHIND THIS REDUC-
TION IN DEGREE-OF-DIFFICULTY IS GIVEN IN APPENDIX A.
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 PRECEDING 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

SAIC
## Baseline Design Parameters

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$</td>
<td>0.97</td>
</tr>
<tr>
<td>$T$</td>
<td>10 YRS</td>
</tr>
<tr>
<td>$A_d$</td>
<td>574 $m^2$</td>
</tr>
<tr>
<td>$A_m$</td>
<td>403 $m^2$</td>
</tr>
<tr>
<td>$Alt$</td>
<td>500 km</td>
</tr>
<tr>
<td>$V_m$</td>
<td>20 km/sec</td>
</tr>
<tr>
<td>$V_D$</td>
<td>10 km/sec</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>0.5 gm/cm$^3$</td>
</tr>
<tr>
<td>$\rho_D$</td>
<td>2.81 gm/cm$^3$</td>
</tr>
<tr>
<td>$h$</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

### Optimal Design (Ballistic Limit)

**Bumper**

- $t_{10} = 0.25$ cm (0.10 IN)

**Wall**

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

**Weight**

- 3800 Kg (8400 lbs)

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MC5 OT 5/87 RWL
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

- \( P_0 = 0.97 \)
- \( T = 10 \) yrs
- \( \text{Alt} = 500 \) 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
- Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

TOTAL CORE MODULE SYSTEM AREA (m\(^2\))
DEBRIS ENVIRONMENT DRIVES DESPITE $P_0$ REDUCTION

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONMENTS 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.
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.
INCREASE IN $P_0$ PRODUCES DRAMATIC WEIGHT INCREASE:
BASELINE MISSION NOT REALIZED

- $P_0 = 0.99$
- $T = 10$ yrs
- $Alt = 500$ 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
- Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

TOTAL CORE MODULE SYSTEM AREA ($m^2$)
GP METHOD CONFIRMS THE MINIMUM WEIGHT

GP METHOD CONFIRMS THE MINIMUM WEIGHT

Minimum weight must lie along this line.

Constraints lie along this line.

Valid region.

- \( d = 0.84 \, \text{cm} \)
- \( V = 10 \, \text{km/sec} \)
- \( h = 10 \, \text{cm} \)
- NYSMITH EQUATION
- CORE MODULE CONFIGURATION

WEIGHT (1000s of kg)

BUMPER THICKNESS \( (t_1) \) (cm)
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.
Optimal design is sensitive to bumper/wall separation.

- $V = 10$ km/sec
- Nysmith Equation
- Core Module Configuration

Core Module Volume Constraint

<table>
<thead>
<tr>
<th>$d$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
</tr>
<tr>
<td>0.84</td>
</tr>
<tr>
<td>0.67</td>
</tr>
</tbody>
</table>

Minimum weight (1000's of kg) vs bumper/wall separation (cm).
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.
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.
OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- \( h = 5 \text{cm} \)
- Nysmith Equation
- Core Module Configuration

MINIMUM WEIGHT (1000s OF KG)

\[ \begin{align*}
&d = 1.00 \text{ cm} \\
&d = 0.84 \text{ cm} \\
&d = 0.67 \text{ cm}
\end{align*} \]

PROJECTILE VELOCITY (km/sec)
OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- \( h = 10 \text{ cm} \)
- Nysmith Equation
- Core Module Configuration

![Graph showing minimum weight (in thousands of kg) vs. projectile velocity (in km/sec) for different values of \( d \) in cm.](image)
OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- h = 15 cm
- Nysmith Equation
- Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

PROJECTILE VELOCITY (km/sec)
OPTIMAL DESIGN IS 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 IMPORTANT ROLE IN DETERMINING THE OPTIMAL DESIGN.
OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

- $V = 10$ Km/sec
- $T = 10$ yrs
- $h = 10$ cm

Nysmith Equation
Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

ACCEPTABLE MISSION RISK ($1 - P_o$)
OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

- $V = 10$ Km/sec
- $T = 10$ yrs
- $h = 5$ cm

Nysmith Equation
Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

ACCEPTABLE MISSION RISK ($1-P_0$)

Area ($m^2$)

688
574
459

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

- $V = 10$ Km/sec
- $T = 10$ yrs
- $h = 15$ cm
- Nysmith Equation
- Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

ACCEPTABLE MISSION RISK ($1 - P_o$)

Area ($m^2$)

- 688
- 574
- 459

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

- $P_0 = 0.97$
- $h = 10 \text{ cm}$
- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Core Module Configuration

MINIMUM WEIGHT (1000s of Kg)

MISSION DURATION (yrs)
OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_0 = 0.95$
- $h = 10\,\text{cm}$
- $V = 10\,\text{km/sec}$
- Nysmith Equation
- Core Module Configuration

\begin{itemize}
  \item $688\,\text{m}^2$
  \item $574\,\text{m}^2$
  \item $459\,\text{m}^2$
\end{itemize}

\begin{tikzpicture}
  \begin{axis}[
    title={MINIMUM WEIGHT (1000s of Kg)},
    xlabel={MISSION DURATION (yrs)},
    ylabel={},
    xmin=0, xmax=35,
    ymin=0, ymax=12,
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    ytick={0,2,4,6,8,10,12},
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    \]
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      (10,4)
      (15,6)
      (20,8)
      (25,10)
      (30,12)
    };
    \end{axis}
\end{tikzpicture}
SECTION IV

GEOMETRIC PROGRAMMING APPLIED TO THE BOEING SUBPREDICTORS.
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
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

\[ t_2 = 1.67 \left( \frac{C_1 \rho_p}{2 \, S_y} \right)^{31} \left( \frac{0.281 \, D \, \rho_p}{\rho_2} \right)^{1/3} \cos(\theta) \]

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

\[ a = 1.33 \sqrt{\text{V}} \ \text{R}_p \ \rho_p \]

\[ b = 8 \ \text{S}_y \ t_1 \ e^{-3.125 \times 10^{-4} \text{V}} / \cos(\theta) \]

\[ c = 1.33 \ \text{R}_p^2 \ \rho_p \]

\[ d = \text{R}_p \ t_1 \ \rho_1 / \cos(\theta) \]

Valid for \( V \leq V_f + 4000 \), where

\[ V_f = \begin{cases} 
4100, & \text{if } t_1 / D \leq 0.4 \\
4986 \ (t_1 / D)^{0.21}, & \text{if } t_1 / D > 0.4
\end{cases} \]
THE PEN4 PREDICTOR (CONTINUED)

\[ V = \text{particle velocity, ft/sec} \]
\[ t_1 = \text{bumper thickness, ft} \]
\[ t_2 = \text{wall thickness, ft} \]
\[ D = \text{particle diameter, ft} \]
\[ R_p = \text{particle radius, ft} \]
\[ \rho_p = \text{projectile density, slugs/ft}^3 \]
\[ \rho_1 = \text{bumper density, slugs/ft}^3 \]
\[ \rho_2 = \text{wall density, slugs/ft}^3 \]
\[ \theta = \text{impact angle from the normal, degrees} \]
\[ S_{y_1} = \text{bumper yield strength, lb/ft}^2 \]
\[ S_{y_2} = \text{wall yield strength, lb/ft}^2 \]

No bumper/wall separation dependency
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_0 )</td>
<td>0.97</td>
</tr>
<tr>
<td>( T )</td>
<td>10 yrs</td>
</tr>
<tr>
<td>( A_d )</td>
<td>574 m²</td>
</tr>
<tr>
<td>( A_m )</td>
<td>403 m²</td>
</tr>
<tr>
<td>( Alt )</td>
<td>500 km</td>
</tr>
<tr>
<td>( V_m )</td>
<td>20 km/sec</td>
</tr>
<tr>
<td>( V_D )</td>
<td>10 km/sec</td>
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<td>( \rho_m )</td>
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<tr>
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<tr>
<td>( \rho_2 )</td>
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</tr>
<tr>
<td>( \theta )</td>
<td>0 degrees</td>
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<td>( S_y_1 )</td>
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</tr>
<tr>
<td>( S_y_2 )</td>
<td>( S_y_1 )</td>
</tr>
</tbody>
</table>
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)

\[ t_2 = \left( \frac{F_1 D}{N} \right)^{1.71} \left( \frac{C}{V} \right)^{2.29} / S^{0.71} \]

where

\[ F_1 = 2.42 \left( \frac{t_1}{D} \right)^{-0.33} + 4.26 \left( \frac{t_1}{D} \right)^{0.33} - 4.18 \]

\[ C = \text{speed of sound in shield, ft/sec} = \sqrt{\frac{E_1}{\rho_1}} \]

\[ E_1 = \text{Youngs Modulus of Elasticity for bumper, lb/ft-sec}^2 \]

\[ \rho_1 = \text{bumper density, lb/ft}^3 \]

\[ V = \text{projectile velocity, ft/sec} \]

\[ S = \text{spacing, inches} \]

\[ D = \text{projectile diameter, inches} \]

\[ t_1 = \text{bumper thickness, inches} \]

\[ t_2 = \text{wall thickness, inches} \]

\[ N = \text{number of plates to penetrate after 1st bumper} \]

No projectile material property dependency
No wall material property dependency

BM09-8/21
THE MODIFIED BURCH PREDICTOR

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

SAME AS THE BURCH PREDICTOR EXCEPT:

\[ F_1 = 2.8 \left( \frac{t_1}{D} \right)^{0.57} + 1.58 \left( \frac{t_1}{D} \right)^{-0.57} \]
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

RATIO OF BUMPER THICKNESS TO PROJECTILE DIAMETER

BURCH DEPENDENT TERM VALUE

ACTUAL

MODIFIED
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.
## Baseline Design Parameters

### Design Assumptions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Description</th>
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<tr>
<td>$P_0$</td>
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<td>Probability of no penetration</td>
</tr>
<tr>
<td>$T$</td>
<td>10 yrs</td>
<td>Mission duration</td>
</tr>
<tr>
<td>$A_d$</td>
<td>574 m$^2$</td>
<td>Debris area</td>
</tr>
<tr>
<td>$A_m$</td>
<td>403 m$^2$</td>
<td>Meteoroid area</td>
</tr>
<tr>
<td>$Alt$</td>
<td>500 km</td>
<td>Average altitude</td>
</tr>
<tr>
<td>$V_m$</td>
<td>20 km/sec</td>
<td>Average meteoroid velocity</td>
</tr>
<tr>
<td>$V_D$</td>
<td>10 km/sec</td>
<td>Average debris velocity</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>0.5 gm/cm$^3$</td>
<td>Meteoroid density</td>
</tr>
<tr>
<td>$\rho_D$</td>
<td>2.81 gm/cm$^3$</td>
<td>Debris density</td>
</tr>
<tr>
<td>$S$</td>
<td>10 cm</td>
<td>Bumper/wall separation</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$7.239 \times 10^{11}$ gm/cm$^2$-sec</td>
<td></td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>2.81 gm/cm$^3$</td>
<td></td>
</tr>
</tbody>
</table>

### Optimal Design (Ballistic Limit)

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

- **Wall**
  - $t_{20} = 0.25$ cm (0.10 in)
  - CMC = 1775 Kg (3905 lb)
  - Weight

---

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.
THE WILKINSON PREDICTOR

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

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

- \( \rho_p \) = 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

SAIC
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.
## Baseline Design Parameters

### Design Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Probability of no penetration</td>
</tr>
<tr>
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<td>Mission duration</td>
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<td>Debris area</td>
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<tr>
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<td>Average debris velocity</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>$0.5 \text{ gm/cm}^3$</td>
<td>Meteoroid density</td>
</tr>
<tr>
<td>$\rho_D$</td>
<td>$2.81 \text{ gm/cm}^3$</td>
<td>Debris density</td>
</tr>
<tr>
<td>$S$</td>
<td>10 cm</td>
<td>(Bumper/wall separation)</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>$2.81 \text{ gm/cm}^3$</td>
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</tr>
<tr>
<td>$\rho_2$</td>
<td>$\rho_1$</td>
<td></td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.401</td>
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</table>

### Optimal Design (Ballistic Limit)

- **Bumper**
  - Thickness: $t_{10} = 0.21 \text{ cm} (0.08 \text{ in})$
- **Wall**
  - Thickness: $t_{20} = 0.21 \text{ cm} (0.08 \text{ in})$
- CMC: 2209 Kg (4860 lb)
  - Weight:

---

BM05-8/21

SAIC
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 ENVIRONMENT DOMINATES THAT OF THE METEOROID.
DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH

MINIMUM "WEIGHT" (cm)

TOTAL CORE MODULE SYSTEM AREA (m²)

SAIC-658D
8/487
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.
DEBRIS ENVIRONMENT DRIVES FOR WILKINSON

MINIMUM "WEIGHT" (cm)

TOTAL CORE MODULE SYSTEM AREA (m²)

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.
VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS

MINIMUM "WEIGHT" (cm)

PROJECTILE VELOCITY (km/sec)

PEN 4

CUMULATIVE PROBABILITY DISTRIBUTION

WILKINSON

MODIFIED BURCH

SAIC-6598
8/487
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

MINIMUM "WEIGHT" (cm)

0.1

0.05

0.0

0.2

0.4

0.6

0.8

1.0

0

5

10

15

20

25

30

SEPARATION BETWEEN BUMPER AND WALL (cm)

MODIFIED BURCH

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

WILKINSON

MODIFIED BURCH

PROJECTILE DIAMETER (cm)

MINIMUM WEIGHT (cm)
SENSITIVITY OF OPTIMAL DESIGN TO THREAT

MINIMUM "WEIGHT" (cm)

PROJECTILE DIAMETER (cm)

WILKINSON

MODIFIED BURCH

SAIC-658C
8/487
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.
WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH
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.
GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION IN 20-30 YEAR RANGE

WILKINSON

MODIFIED BURCH

MINIMUM WEIGHT (cm)

MISSION DURATION (YEARS)
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.
GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS

WILKINSON PREDICTOR
MODIFIED BURCH

WALL

V=16 KM SEC

BUMPER

V=10 KM SEC

SAIC-6584
9/4/87
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-DIFFI-
CULTY 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

ERROR IN WEIGHT (%)

BUMPER THICKNESS (cm)

MODIFIED BURCH
WILKINSON
SECTION V

GEOMETRIC PROGRAMMING APPLIED TO

THE BOEING PREDICTOR.
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
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.
### BASELINE DESIGN PARAMETERS

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<tr>
<td>$T$</td>
<td>10 yrs</td>
<td></td>
<td>Mission duration</td>
</tr>
<tr>
<td>$A_d$</td>
<td>574 m²</td>
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<td>Debris area</td>
</tr>
<tr>
<td>$A_m$</td>
<td>403 m²</td>
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<td>Meteoroid area</td>
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<td>Alt</td>
<td>500 km</td>
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<td>Average altitude</td>
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<tr>
<td>$V_m$</td>
<td>20 km/sec</td>
<td></td>
<td>Average meteoroid velocity</td>
</tr>
<tr>
<td>$V_D$</td>
<td>10 km/sec</td>
<td></td>
<td>Average debris velocity</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>0.5 gm/cm³</td>
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<td>Meteoroid density</td>
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<td>$\rho_D$</td>
<td>2.81 gm/cm³</td>
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<td>Debris density</td>
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<td>$S$</td>
<td>10 cm</td>
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<td>Bumper/wall separation</td>
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<tr>
<td>$E_1$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$S_{y_1}$</td>
<td>7344000 lb/ft²</td>
<td></td>
<td>(51 KSI)</td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>$\rho_1$</td>
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<td></td>
</tr>
<tr>
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<td>$S_{y_1}$</td>
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<td></td>
</tr>
<tr>
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<td>OPTIMAL DESIGN (BALLISTIC LIMIT)</td>
<td>BUMPER</td>
<td>WALL</td>
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<tr>
<td>---------------------------------</td>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>$t_{10}$ = 0.09 cm (0.04 in)</td>
<td>CMC weight = 2979 Kg (6554 lb)</td>
<td></td>
<td></td>
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<tr>
<td>$t_{20}$ = 0.49 cm (0.19 in)</td>
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</tbody>
</table>
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.
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
GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR.
GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION FOR THE BOEING PREDICTOR

MINIMUM "WEIGHT" (cm)

BUMPER/WALL SEPARATION (cm)

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

MINIMUM "WEIGHT" (cm)

ACCEPTABLE MISSION RISK

SAIC-664H 8/11/67
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.
SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR
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

OPTIMAL RATIO

PROJECTILE DIAMETER (cm)

WALL

BUMPER

SAIC-664C
8/11/87
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.
SECTION VI

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

#### Design Assumptions

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<tr>
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<tr>
<td>Alt</td>
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<td>Average altitude</td>
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<tr>
<td>$\rho_m$</td>
<td>0.5 gm/cm$^3$</td>
<td>Meteoroid density</td>
</tr>
<tr>
<td>$\rho_D$</td>
<td>2.81 gm/cm$^3$</td>
<td>Debris density</td>
</tr>
<tr>
<td>$S$</td>
<td>10 cm</td>
<td>Bumper/wall separation</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>2.81 gm/cm$^3$</td>
<td></td>
</tr>
<tr>
<td>$E_1$</td>
<td>$7.239 \times 10^{11}$ gm/cm$\cdot$sec$^2$</td>
<td></td>
</tr>
<tr>
<td>$S_y_1$</td>
<td>7344000 lb/ft$^2$ (51 Ksl)</td>
<td></td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>$\rho_1$</td>
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<tr>
<td>$S_y_2$</td>
<td>$S_y_1$</td>
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<tr>
<td>$L_2$</td>
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<tr>
<td>$\theta$</td>
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</table>

#### Optimal Design

- **Bumper**
  - $t_{10} = 0.16$ cm (0.06 in)

- **Wall**
  - $t_{20} = 0.59$ cm (0.23 in)
  - CMC Weight: 3837 Kg (8441 lb)
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 SKEewed TOWARD THE HIGHER VELOCITIES.
METEOROID VELOCITY PROBABILITY DISTRIBUTION

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.
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

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

MINIMUM "WEIGHT" (cm)

BUMPER/WALL SEPARATION (cm)

SAIC-664B
8/11/87
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.
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.
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

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

- 60 DEG. INCL.

MINIMUM "WEIGHT" (cm)

ACCEPTABLE MISSION RISK

SAIC-664H
8/11/87
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

MISSION DURATION (YEARS)

PROJECTILE DIAMETER (cm)
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.
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.
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

- ASSUMED LAUNCH COST = $6000/kg
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.
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

[Graphs showing mission duration, projectile diameter, optimal ratio, and launch cost as functions of time and size.]

SAIC
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.
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, PIECEWISE 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 POSYNOMIAL REQUIREMENT.
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.
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
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
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
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)
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
SURVIVABILITY AND PREDICTOR REFERENCES


SURVIVABILITY AND PREDICTOR REFERENCES (CONTINUED)


OPTIMIZATION REFERENCES


2. AVRIEL, M., ADVANCES IN GEOMETRIC PROGRAMMING, PLENUM PRESS, NEW YORK, 1980.


5. AVRIEL, M., NONLINEAR PROGRAMMING ANALYSIS AND METHODS, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NEW JERSEY, 1976.
OPTIMIZATION REFERENCES
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SECTION X

APPENDICES
A. MATHEMATICS
**GP APPLIED TO NYSMITH**

Consider the Nysmith Equation:

\[ t_2 = 5.08V^{-278}d^{2.92/\left(t_1^{0.528}h^{1.39}\right)} , \]

with inequality constraints

\[ t_1/d \leq 0.5 \ , \ t_2/d \leq 1.0 \]

Note that if

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

\[ \frac{t_1}{d} \leq 0.5 \Rightarrow \]

\[ \frac{t_2}{d} > 5.08V^{-278}(0.24hV^{-0.2})^{1.39}/\left((0.5)^{0.528}h^{1.39}\right) \ \text{or} , \]

\[ \frac{t_2}{d} > 1.0 \]

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

\[ d \leq 0.24hV^{-0.2} \]

Letting the idealized "weight" be denoted by \( w \), one has:

\[ w = t_1 + t_2 \]

Substituting Nysmith, one has:

\[ w = t_1 + 5.08V^{-278}d^{2.92/\left(t_1^{0.528}h^{1.39}\right)} , \]

with inequality constraints:

\[ \frac{2t_1}{d} \leq 1.0 \ , \ 5.08V^{-278}d^{1.92/\left(t_1^{0.528}h^{1.39}\right)} \leq 1.0 \]
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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:
\[ \delta_1 = 0.35 \quad \delta_2 = 0.65 , \]

- \[ w_0 = 5.52V^{18}d^{0.91}/h^{0.91} \] is the minimum "weight".
- \[ t_\theta = 1.93V^{18}d^{0.91}/h^{0.91} \] is the optimal bumper thickness, and
- \[ t_\phi = 3.59V^{18}d^{0.91}/h^{0.91} \] is the optimal wall thickness.

Note that the optimal ratios are given by:
\[ \frac{t_\theta}{t_\phi + t_\phi} = 0.35 = \delta_1 , \quad \frac{t_\phi}{t_\phi + t_\phi} = 0.65 = \delta_2 \]

Furthermore, this analytic solution is valid for
\[ d \leq 0.23hV^{-0.2} \] Why?

\[ h \geq 4.35dV^{0.2} \Rightarrow t_\theta \leq 1.93V^{18}d^{0.91}(4.35dV^{0.2})^{-0.91} \] or

\[ t_\phi \leq 0.5d , \quad \text{as desired. Also,} \]
\[ t_\phi = 1.86t_\theta < d , \quad \text{as required.} \]
Thus the constrained problem need only be solved for

\[ 0.23hV^{-0.2} \leq d \leq 0.24hV^{-0.2} \]

B. Constrained Optimization

The constrained dual GP problem may be written:

maximize: \[ v(\delta) = \left(\frac{1}{\delta_1}\right)^{\delta_1} (c_1/\delta_2)^{\delta_2} (c_2)^{\delta_{11}'} (c_4)^{\delta_{12}'} \]
subject to: \[ \delta_1 + \delta_2 = 1 \]
\[ \delta_1 - 0.528\delta_2 + \delta_{11}' - 0.528\delta_{12}' = 0 \]
where: \[ c_1 \text{ is defined as in part A} \]
\[ c_2 = c_1/d \]
\[ c_3 = 2/d \]

This is a 2 degree-of-difficulty problem, since there are 2 equations and 4 unknowns. It is solved numerically.
DERIVATION OF CORE MODULE CONFIGURATION WEIGHT

Let:  \( r_{12} = \) radius of a core module

\[
\begin{align*}
  r_{22} &= r_{12} + t_2 \\
  r_{11} &= r_{22} + h \\
  r_{21} &= r_{11} + t_1 \\
  L &= \text{core module length}
\end{align*}
\]

Then,

\[
w = \pi L [p_1(r_{21}^2 - r_{11}^2) + p_2(r_{22}^2 - r_{12}^2)]
\]

is the total core module weight.
GP APPLIED TO THE CMC WEIGHT FUNCTION

Let: \( r_{12} = 210.8 \) cm
\[ L = 1356.7 \text{ cm} \]
\( \rho_1 = \rho_2 = 2.81 \text{ gm/cm}^3 \)

Applying the Nysmith equation, one has:
\[ w_{CMC} = 12t_i^2 + c_1t_i + 122c_2t_i^{0.472} + 25700c_2t_i^{-0.528} + 310c_2t_i^{-1.06} \]

where:
\( c_1 = 5059 + 24h \), and
\( c_2 = \sqrt[278]d^{2.92}/h^{1.39} \)

The chosen approximate weight is given by:
\[ w_{C_{MC, app}} = c_1t_i + 25700c_2t_i^{-0.528} \]

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:
\( \delta_1 = 0.346 \), \( \delta_2 = 0.654 \)
\[ w_0 = 1459 c_1^{0.346} c_2^{0.654} \]

\[ t_1 = \frac{\delta_1 w_0}{c_1} = 505 \left( \frac{c_2}{c_1} \right)^{0.654} \]

\[ t_2 = 1.89 t_1 = 954 \left( \frac{c_2}{c_1} \right)^{0.654} \]
GP APPLIED TO WILKINSON

Recall that:

\[
\frac{D\rho_p}{\rho_1 t_1} \leq 1 \Rightarrow t_2 = 0.364D^3\rho_p V_N/(L_2S^2\rho_2) \quad \text{and},
\]

\[
\frac{D\rho_p}{\rho_1 t_1} > 1 \Rightarrow t_2 = 0.364D^4\rho_p^2 V_N/(L_2S^2\rho_1\rho_2)
\]

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:

\[
c_1 = 0.364D^4\rho_p^2 V_N/(L_2S^2\rho_1\rho_2)
\]

The dual GP problem may be written:

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

subject to: \( \delta_1 + \delta_2 = 1 \)

\( \delta_1 - \delta_2 = 0 \)

Thus, \( \delta_1 = \delta_2 = 1/2 \) , and

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

\[
t_1 = t_2 = 0.604 \frac{D^2\rho_p}{S} \left( \frac{V_N}{L_2\rho_1\rho_2} \right)^{1/2}
\]
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Thus, the procedure is the following:

1) Determine \( t_{i_0} \), \( t_{2_0} \) from the above equation.

2) Compute \( \frac{D \rho_E}{\rho_1 t_{i_0}} \).

3) If \( \frac{D \rho_E}{\rho_1 t_{i_0}} > 1 \), then quit. Optimal design is \( (t_{i_0}, t_{2_0}) \).

4) If \( \frac{D \rho_E}{\rho_1 t_{i_0}} \leq 1 \), optimal design is \( (t_{i_0}, t_{2_0}, \left( \frac{D \rho_E}{\rho_1 t_{i_0}} \right)) \).

Optimal Ratios for Wilkinson

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

\[
\frac{D \rho_E}{\rho_1 t_{i_0}} \leq 1, \text{ or } \frac{D \rho_E}{\rho_1} 
\]

This implies:

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

\[
D \geq 1.668 \left( \frac{L_2 \rho_2}{V_N \rho_1} \right)^{1/2} 
\]
GP APPLIED TO MODIFIED BURCH

Recall the Modified Burch Predictor:
\[ t_2 = CK \], where
\[ C = \left( \frac{D}{N} \right)^{1.71} \left( \frac{C}{V} \right)^{2.29} / \delta^{0.71} \], and
\[ K = 2.8(t_1/D)^{0.57} + 1.58(t_1/D)^{-0.57} \]

Thus,
\[ w = t_1 + 2.8CD^{-0.57}t_1 + 1.58CD^{0.57}t_1 \] is the idealized weight.

Thus, the GP dual problem may be written:

Maximize:
\[ v(\delta) = \left( \frac{1}{\delta_1} \right)^{\delta_1} \left( \frac{2.8CD^{-0.57}}{\delta_2} \right)^{\delta_2} \left( \frac{1.58CD^{0.57}}{\delta_3} \right)^{\delta_3} \]
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 \( t_1 = \delta_1(\max(v(\delta))) \).

4) Let \( t_2 = \max(v(\delta)) - t_1 \).
OPTIMAL DESIGN ALGORITHM FOR BOEING PREDICTOR

1. Compute optimal design for PEN4 Predictor, \((t_{1p}, t_{2p})\).

2. Check against PEN4 constraint, \(V \leq V_f\left[\frac{t_{1p}}{D}\right] + 4000\) ?

3. If satisfied, the optimal design is \((t_1, t_2) = (t_{1p}, t_{2p})\).

4. Else, compute optimal designs for Modified Burch, \((t_{1B}, t_{2B})\), and Wilkinson, \((t_{1w}, t_{2w})\) Predictors.

5. Compute Wilkinson wall induced by optimal Modified Burch bumper, \(t_{2w}(t_{1B})\).

6. Compute Burch wall induced by optimal Wilkinson bumper, \(t_{2B}(t_{1w})\).

7. Find \((t_1, t_2) = \min_{t_{1+B}} \left[\left(t_{1B}, \max(\max(t_{2B}, t_{2w}(t_{1B}))), (t_{1w}, \max(t_{2w}, t_{2B}(t_{1w})))\right]\).
B. COMPUTER CODES
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.
<table>
<thead>
<tr>
<th>NO. OF CASES</th>
<th>SURFACE AREA IN SQ. METERS</th>
<th>DURATION IN YEARS</th>
<th>PROB. OF NO PENETRATION</th>
<th>ALT. IN KM</th>
<th>DENSITY IN GM/CUBIC CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400.</td>
<td>10.</td>
<td>.97</td>
<td>500.</td>
<td>.5</td>
</tr>
</tbody>
</table>
INPUT

SURFACE AREA IN SQUARE METERS = 400.0000
MISSION DURATION IN YEARS = 10.0000
PROB. OF NO PENETRATION = 0.970000
ALTITUDE IN KILOMETERS = 500.0000
PROJ. DENSITY IN GM/CUBIC CM = 0.5000000

OUTPUT

DIAM = 0.4614225
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,*)' 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
  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(IO,*)' MASS IS TOO SMALL'
    GO TO 10
  ENDIF
  IF(F.GT.-7.103.AND.F.LT.-4.403)THEN
    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(IO,*)' MASS IS TOO LARGE'
    GO TO 10
  ENDIF
  D=(1.91*XM/DENS)**.333
  WRITE(IO,*)' DIAM=',D
CONTINUE
END
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.
<table>
<thead>
<tr>
<th>NO. OF CASES</th>
<th>PROJECTED AREA IN SQ. METERS</th>
<th>DURATION IN YEARS</th>
<th>PROB. OF NO PENETRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>574.</td>
<td>10.</td>
<td>.97</td>
</tr>
</tbody>
</table>
INPUT

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

OUTPUT

DIAM = 0.8446254
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(IO,*);
WRITE(10,*)' PROJ. AREA IN SQUARE METERS = ',AP
WRITE(10,*)' MISSION DURATION IN YEARS = ',T
WRITE(10,*)' PROB. OF NO PENETRATION = ',PO
WRITE(IO,*)' OUTPUT'
WRITE(10,*)
FLUX=-I.*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(IO,*)' DIAM=',D
CONTINUE
END

ORIGINAL PAGE IS OF POOR QUALITY.
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.
<table>
<thead>
<tr>
<th>NUMBER OF CASES</th>
<th>NYSMITH PREDICTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.</td>
<td>PROJ. VELOCITY IN KM/SEC</td>
</tr>
<tr>
<td>10.</td>
<td>PROJ. DIAMETER IN CM</td>
</tr>
<tr>
<td>10.</td>
<td>BUMPER/WALL SEPARATION IN CM</td>
</tr>
<tr>
<td>10.</td>
<td>BOEING PREDICTOR</td>
</tr>
<tr>
<td>2.81</td>
<td>PROJ. DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>BUMPER DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>WALL DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>10.</td>
<td>BUMPER/WALL SEPARATION IN CM</td>
</tr>
<tr>
<td>0.84</td>
<td>WALL MATERIAL CONSTANT</td>
</tr>
<tr>
<td>7344000.</td>
<td>BUMPER YIELD STRENGTH IN LB/SQUARE FOOT</td>
</tr>
<tr>
<td>7344000.</td>
<td>WALL YIELD STRENGTH IN LB/SQUARE FOOT</td>
</tr>
<tr>
<td>0.</td>
<td>IMPACT ANGLE FROM NORMAL</td>
</tr>
<tr>
<td>0.85</td>
<td>NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER</td>
</tr>
<tr>
<td>7.239E11</td>
<td>YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC</td>
</tr>
<tr>
<td>3</td>
<td>MADDEN PREDICTOR</td>
</tr>
<tr>
<td>10.</td>
<td>PROJ. VELOCITY IN KM/SEC</td>
</tr>
<tr>
<td>10.</td>
<td>PROJ. DIA. IN CM</td>
</tr>
<tr>
<td>10.</td>
<td>BUMPER/WALL SEPARATION IN CM</td>
</tr>
<tr>
<td>2.81</td>
<td>PROJ. DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>BUMPER/WALL DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>4</td>
<td>WILKINSON PREDICTOR</td>
</tr>
<tr>
<td>10.</td>
<td>PROJ. VELOCITY IN KM/SEC</td>
</tr>
<tr>
<td>0.84</td>
<td>PROJ. DIA. IN CM</td>
</tr>
<tr>
<td>2.81</td>
<td>PROJ. DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>BUMPER DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>WALL DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>10.</td>
<td>BUMPER/WALL SEPARATION IN CM</td>
</tr>
<tr>
<td>0.401</td>
<td>WALL MATERIAL CONSTANT</td>
</tr>
<tr>
<td>5</td>
<td>BURCH PREDICTOR</td>
</tr>
<tr>
<td>10.</td>
<td>PROJ. VELOCITY IN KM/SEC</td>
</tr>
<tr>
<td>0.84</td>
<td>PROJ. DIA. IN CM</td>
</tr>
<tr>
<td>2.81</td>
<td>BUMPER DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>10.</td>
<td>BUMPER/WALL SEPARATION IN CM</td>
</tr>
<tr>
<td>0.</td>
<td>IMPACT ANGLE FROM NORMAL</td>
</tr>
<tr>
<td>0.85</td>
<td>NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER</td>
</tr>
<tr>
<td>7.239E11</td>
<td>YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC</td>
</tr>
<tr>
<td>6</td>
<td>PEN4 PREDICTOR</td>
</tr>
<tr>
<td>1.</td>
<td>PROJ. VELOCITY IN KM/SEC</td>
</tr>
<tr>
<td>0.84</td>
<td>PROJ. DIA. IN CM</td>
</tr>
<tr>
<td>2.81</td>
<td>PROJ. DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>BUMPER DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>2.81</td>
<td>WALL DENSITY IN GM/CUBIC CM</td>
</tr>
<tr>
<td>7344000.</td>
<td>BUMPER YIELD STRENGTH IN LB/SQUARE FOOT</td>
</tr>
<tr>
<td>7344000.</td>
<td>WALL YIELD STRENGTH IN LB/SQUARE FOOT</td>
</tr>
<tr>
<td>0.</td>
<td>IMPACT ANGLE FROM NORMAL</td>
</tr>
</tbody>
</table>
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-02 CM
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
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
WALL THICKNESS = 0.00000000E+00 CM
MIN. WEIGHT = 2.1661645E-02 CM
CMC MIN. WEIGHT = 222.9546 KG
OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5.IN',ACCESS='SEQUENTIAL')
OPEN(UNIT=11,TYPE='NEW',NAME='IMPACTS.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
  READ(10,*)V
  READ(10,*)D
  READ(10,*)H
  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
  CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
  WRITE(11,*)' OUTPUT'
  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
  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
  WRITE(11,*)' BOEING'
  WRITE(11,*)' INPUT'
  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 YOUNG'S MODULUS IN GM/CM-SQUARE',
& ' SEC = ',E1
CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XT2,SY1,SY2,THETA,
& XN,E1,T1,T2,WT,WTCMC)
WRITE(11,*)' OUTPUT'
WRITE(11,*)
WRITE(11,*)' BUMPER THICKNESS = ',TI,'CM'
WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
WRITE(11,*)' OUTPUT'
WRITE(11,*)
WRITE(11,*)
GO TO 10
READ(IO,*)V
READ(IO,*)D
READ(IO,*)RHOP
READ(IO,*)S
READ(IO,*)RHO
WRITE(11,*)' MADDEN'
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
CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
WRITE(11,*)' OUTPUT'
WRITE(11,*)
WRITE(11,*)' BUMPER THICKNESS = ',TI,'CM'
WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
WRITE(11,*)' OUTPUT'
WRITE(11,*)
WRITE(11,*)
GO TO 10
READ(IO,*)V
READ(IO,*)D
READ(IO,*)RHOP
READ(IO,*)RHO1
READ(IO,*)RHO2
READ(IO,*)S
READ(IO,*)XT2
WRITE(11,*)
WRITE(11,*)' WILKINSON'
WRITE(11,*)
WRITE(11,*)' PROJECTILE VELOCITY IN KM/SEC = ',V
MODIFIED BURCH

INPUT

PROJECTILE VELOCITY IN KM/SEC = ',V
PROJECTILE DIAMETER IN CM = ',D
BUMPER DENSITY IN GM/CUBIC CM = ',RHOP
BUMPER/WALL SEPARATION IN CM = ',S
IMPACT ANGLE FROM NORMAL IN DEGREES : ',THETA
NUMBER OF PLATES TO PENETRATE AFTER FIRST',
BUMPER-THICKNESS = ',TI,'CM'
WALL THICKNESS = ',T2,'CM'
MIN. WEIGHT = ',WT,'CM'
CMC MIN. WEIGHT = ',WTCMC,'KG'

OUTPUT

BUMPER YOUNGS MODULUS IN GM/CM-SQUARE', SEC = ',E1

CALL BURCH(V,D,RHOP,RH01,S,THETA,XN,E1,T1,T2,WT,WTCMC)

BUMPER THICKNESS = ',TI,'CM'
WALL THICKNESS = ',T2,'CM'
MIN. WEIGHT = ',WT,'CM'
CMC MIN. WEIGHT = ',WTCMC,'KG'

GO TO 10
IMPACTS$MAIN 0172
0173
0174
0175
0176
0177
0178
0179
0180
0181
0182
0183
0184
0185
0186
0187
0188
0189
0190
0191
0192
0193
0194
0195
0196
0197
0198
0199
0200
0201
READ(10,*), RH02
READ(10,*), SY1
READ(10,*), SY2
READ(10,*), THETA
WRITE(11,*), ' PEN4'
WRITE(11,*), ' INPUT'
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 = ', RH01
WRITE(11,*), ' WALL DENSITY IN GM/CUBIC CM = ', RH02
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
CALL PEN4(V, D, RHOP, RH01, RH02, SY1, SY2, THETA, TI, T2, WT, WTCMC)
WRITE(11,*), ' OUTPUT'
WRITE(11,*), ' BUMPER THICKNESS = ', TI, ' CM'
WRITE(11,*), ' WALL THICKNESS = ', T2, ' CM'
WRITE(11,*), ' MIN. WEIGHT = ', WT, ' CM'
WRITE(11,*), ' CMC MIN. WEIGHT = ', WTCMC, ' KG'
GO TO 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'
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
CONTINUE
RETURN
END
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,TIP)
WT=T1P+T2P

IF(NITSP.EQ.1)THEN
  T1P1=1.1*T1P
  T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
  WT1=T1P1+T2P1
ENDIF

IF(WT1.GT.WT)THEN
  TIP1=0.82*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
    TIP=T1P1
    T2P=T2P1
    WT=WT1
    NP1=NP1+1
    IF(NP1.EQ.100)THEN
      WRITE(11,*)'NO CONVERGENCE IN PEN4'
      GO TO 557
    ENDIF
    T1P=0.9*T1P1
    T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
    WT1=T1P1+T2P1
    GO TO 590
  ENDIF
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
  T1P=0.9*T1P1
  T2P=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
0058   ENDIF
0059   ENDIF
0060  601   CONTINUE 
0061     D=30.48*D 
0062     RHOP=RHOP/1.94 
0063     RHO1=RHO1/1.94 
0064     RHO2=RHO2/1.94 
0065     TIP=30.48*TIP 
0066     T2P=30.48*T2P 
0067     IF(TIP/D.LE.0.4)VF=4100 
0068     IF(TIP/D.GT.0.4)VF=4986*(TIP/D)**0.21 
0069     VF=VF+4000. 
0070     IF(V.LE.VF)THEN 
0071       WRITE(11,*)'INSIDE OF PEN4 LIMITS' 
0072       T1=TIP 
0073       T2=T2P 
0074     GO TO 1102 
0075   ENDIF 
0076  557   CONTINUE 
0077 ***** WILKINSON *****
0078     V=V/3280. 
0079     T1=0.604*D**2.*RHOP/S 
0080     T1=T1*SQR(T(V/(XL2*RHO1*RHO2))) 
0081     RATIO=D*RHOP/(T1*RHO1) 
0082     IF(RATIO.GT.1.0)T2=T1 
0083     IF(RATIO.LE.1.0)T2=T1/RATIO 
0084 ***** MODIFIED BURCH *****
0085     VB=V*3280. 
0086     DB=D/2.54 
0087     CM=SQR(EI/RHO1) 
0088     CM=CM/30.48 
0089     SB=S/2.54 
0090     IF(THETA.LE.0.001)GO TO 125 
0091     CHI=TAN(THETA)-0.5 
0092     F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0 
0093     F2=F2+(1.7-12.*T1B/D)*CHI 
0094     F3=0.32*(T1B/D)**0.83 
0095     F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0 
0096     T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29 
0097     T2F=T2F*(D/S)**0.71 
0098     T2N=F3*(CM/V)**1.33*D/XN 
0099     IF(T2N.GE.T2F)T2B=T2N 
0100     IF(T2N.LT.T2F)T2B=T2F 
0101     T2B=T2B*2.54 
0102     IF(T2B.GT.T2)NREGION=3 
0103     IF(T2B.GT.T2)T2=T2B 
0104     GO TO 155 
0105  125   CONTINUE 
0106     T1B1=T1/2.54 
0107     NITSB=0 
0108     XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71 
0109     VDELTAB=0.0 
0110     DELTA3=0.52 
0111  1099  DELTA2=2.33*(1.-1.57*DELTA3) 
0112     DELTA1=1.33*(2.*DELTA3-1.) 
0113     VDELTAIN=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2 
0114     VDELTAIN=VDELTAIN*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
IF(VDELTA1.LT.VDELTA)THEN
  DELTA1=1.33*(2.*DELTA3-1.04)
  TIB=DELTA1*VDELTA
  T2B=VDELTA-TIB
ENDIF
GO TO 499
VDELTA=VDELTA1
DELTA3=DELTA3+0.02
IF(DELTA3.GT.0.63)THEN
  TIB=DELTA1*VDELTA
  T2B=VDELTA-TIB
  GO TO 499
ENDIF
GO TO 1099
CONTINUE
STOP

COMPARISON OF MODIFIED BURCH AND WILKINSON *****
CONTINUE
T1OW=TI/2.54
F1OW=1.58*(DB/T1OW)**0.57+2.80*(T1OW/DB)**0.57
T2BT1OW=(F1OW/XN)**1.71*(CM/VB)**2.29*DB**1.71
T2BT1OW=T2BT1OW/SB**0.71
T2BT10W=T2BT1OW*2.54
RATIOB=(DB*RHOP)/(RH01*TB)
T2WT10B=0.364*DB**3.*RHOP*V/(XL2*RH02*S**2.*)
IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
IF(T2BT10W.GT.T2)T2=T2BT10W
T1B=T2B*2.54
IF(T2WT10B.GT.T2B)T2B=T2WT10B
T1B=TIB
T2=T2B
ENDIF
CONTINUE
IF(T2.LE.0.01)THEN
  WRITE(11,*)'PRESSURE CONSTRAINT ON WALL IN EFFECT'
  T2=3099.1/SIGMA
ENDIF
WT=TI+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.)
WTMC=RH01*VB+RH02*VW
RETURN
END
FUNCTION FT2B(DB,TIB,XN,CM,VB,SB)
FI=2.42*(DB/TIB)**0.33+4.26*(TIB/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**

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**Total Space Allocated**

| 167 |

**ENTRY POINTS**

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FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP)
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/RH02)**0.33
XK1=XK1*COS(THETA)
C1P1=(A-B*TIP)/(C+D1*TIP)
IF(C1P1.LE.0.001)THEN
   FT2P=0.0
   GO TO 999
ENDIF
FT2P=XK1*C1P1**0.31
RETURN
END
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

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FUNCTIONS AND SUBROUTINES REFERENCED

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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
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

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Total Space Allocated 181

ENTRY POINTS

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FUNCTIONS AND SUBROUTINES REFERENCED

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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*(TIB/D)+(5.*TIB/D-1.6)*CHI**3.0
F2=F2+(1.7-12.*TIB/D)*CHI
F3=0.32*(TIB/D)**0.83
F3=F3+0.48*(TIB/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
CONTINUE
NITSB=0
XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
VDELTA=0.0
DELTA3=0.52
DELTAA=2.33*(1.-1.57*DELTA3)
DELTA1=1.33*(2.*DELTA3-1.)
VDELTA1=VDELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
IF(VDELTA1.LT.VDELTA1)THEN
   TI=DELTA1*VDELTA
   T2=VDELTA-T1
   GO TO 499
ENDIF
VDELTA=VDELTA1
DELTA3=DELTA3+0.02
IF(DELTA3.GT.0.63)THEN
   TI=DELTA1*VDELTA
   T2=VDELTA-T1
   GO TO 499
ENDIF
ENDIF
GO TO 1099
CONTINUE
T1=T1*2.54
T2=T2*2.54
WT=T1+T2
R12=211.
R22=211.+T2
R11=211.+T2+S
R21=211.+TI+T2+S
VB=4.27*(R21**2.-R11**2.)
WV=4.27*(R22**2.-R12**2.)
WTCMC=RHO1*VB+2.81*WV
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=RH01*1.94
    RHO2=RH02*1.94
    NITSP=0
    NITSP=NITSP+1
    NPI=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
        T1PI=I.I*TIP
        T2PI=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
        WT1=T1PI+T2PI
    ENDIF
    IF(WT1.GT.WT)THEN
        TIP1=0.82*TIP1
        T2PI=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
        WT1=TIPI+T2PI
        IF(WT1.GT.WT)THEN
            GO TO 599
        ELSE
            TIP=TIP1
            T2P=T2PI
            WT=WT1
            NPI=NPI+1
            IF(NPI.EQ.IOO)THEN
                WRITE(11,*)'NO CONVERGENCE IN PEN4'
                GO TO 555
            ENDIF
            T1PI=I.I*TIP
            T2PI=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
            WT1=TIPI+T2PI
            IF(WT1.GT.WT)THEN
                GO TO 599
            ELSE
                NPI=NPI+1
                IF(NPI.EQ.IOO)THEN
                    WRITE(11,*)'NO CONVERGENCE IN PEN4'
                    GO TO 555
                ENDIF
                GO TO 577
            ENDIF
        ELSE
            TIP=TIPI
            T2P=T2PI
            WT=WT1
            T1PI=I.I*TIP
            T2PI=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
            WT1=TIPI+T2PI
            IF(WT1.GT.WT)THEN
                GO TO 599
            ELSE
                NPI=NPI+1
                IF(NPI.EQ.IOO)THEN
                    WRITE(11,*)'NO CONVERGENCE IN PEN4'
                    GO TO 555
                ENDIF
                GO TO 577
            ENDIF
        ENDIF
    ELSE
        TIP=TIPI
        T2P=T2PI
        WT=WT1
        T1PI=I.I*TIP
        T2PI=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
        WT1=TIPI+T2PI
        IF(WT1.GT.WT)THEN
            GO TO 599
        ELSE
            NPI=NPI+1
            IF(NPI.EQ.IOO)THEN
                WRITE(11,*)'NO CONVERGENCE IN PEN4'
                GO TO 555
            ENDIF
            GO TO 577
        ENDIF
    ENDIF

END
IF(TIP/D.LE.0.4)VF=4100
IF(TIP/D.GT.0.4)VF=4986*(TIP/D)**0.21
VF=VF+4000.
IF(V.GT.VF)THEN
WRITE(I1,*)'OUTSIDE OF PEN4 LIMITS'
GO TO 1100
ENDIF
T1=TIP
T2=T2P
CONTINUE
WT=TI+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
RETURN
END
**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 (500KM60DEG.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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### 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**

**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)
CONTINUE
DO 24 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
   READ(IO,*) D
   READ(IO,*) H
   WRITE(11,*) ' NYSMITH
   WRITE(11,*)' INPUT'
   WRITE(11,*)' PROJECTILE DIAMETER IN CM = ', D
   WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ', H
   T1=T1+TI*XPV(J)
   T2=T2+T2*XPV(J)
CONTINUE
T1=T1
T2=T2
WT=TI+T2
WTCMC=TI**2.+2.*TI*(211.+T2+H)+T2**2.+422.*T2
WRITE(11,*)' OUTPUT'
WRITE(11,*)' BUMPER THICKNESS = ', TI,' CM'
WRITE(11,*)' WALL THICKNESS = ', T2,' CM'
WRITE(11,*)' MIN. WEIGHT = ', WT,' CM'
WRITE(11,*)' CMC MIN. WEIGHT = ', WTCMC,' KG'
WTCMC=12.*WTCMC
WRITE(11,*)' BUMPER THICKNESS : ', TI,' CM'
WRITE(11,*)' WALL THICKNESS = ', T2,' CM'
WRITE(11,*)' MIN. WEIGHT = ', WT,' CM'
WRITE(11,*)' CMC MIN. WEIGHT = ', WTCMC,' KG'
GO TO 10
READ(10,*) D
READ(10,*) RHOP
READ(10,*) RH01
READ(10,*) RH02
READ(10,*) S
READ(10,*) XL2
READ(10,*) SY1
READ(10,*) SY2
READ(10,*) THETA
READ(10,*) XN
Input

BOEING'

PROJECTILE DIAMETER IN CM = ',D
PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
BUMPER DENSITY IN GM/CUBIC CM = ',RH01
WALL DENSITY IN GM/CUBIC CM = ',RH02
BUMPER/WALL SEPARATION IN CM = ',S
WALL MATERIAL CONSTANT = ',XL2
BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
NUMBER OF PLATES TO PENETRATE AFTER FIRST', BUMPER = ',XN
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE', SEC = ',EI

WRITE(11,*),BOEING'
WRITE(11,*)' INPUT'
WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RH01
WRITE(11,*)' WALL DENSITY IN GM/CUBIC CM = ',RH02
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 = ',EI

WRITE(11,*)' OUTPUT'
WRITE(11,*),BOEING'
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'

GO TO 10
READ(10,*)D
READ(10,*)RHOP
READ(10,*)S
READ(10,*)RH02
WRITE(11,*)' MADDEN'
WRITE(11,*)' INPUT'
WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
IMPACTV$MAIN

0115 WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0116 WRITE(11,*)' BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0117 WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S

0119 T1T=0.0
0120 T2T=0.0
0121 DO 46 J=1,16
0122 V=FLOAT(J)
0123 CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0124 T1T=T1T+T1*XPV(J)
0125 T2T=T2T+T2*XPV(J)
0126 CONTINUE

0127 T1=T1T
0128 T2=T2T
0129 WT=T1+T2
0130 R12=211.
0131 R22=211.+T2
0132 R11=211.+T2+S
0133 R21=211.+T1+T2+S
0134 VB=4.27*(R21**2.-R11**2.)
0135 VW=4.27*(R22**2.-R12**2.)
0136 WTCMC=RHO*(VB+VW)
0137 WRITE(11,*)' OUTPUT'

0138 WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0139 WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0140 WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0141 WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'

0142 WRITE(11,*)
0143 WRITE(11,*)
0144 WRITE(11,*)
0145 WRITE(11,*)

0146 GO TO 10

0147 READ(10,*)D
0148 READ(10,*)RHOP
0149 READ(10,*)RHO1
0150 READ(10,*)RHO2
0151 READ(10,*)S
0152 READ(10,*)XL2

0153 WRITE(11,*)' WILKINSON'

0154 WRITE(11,*)
0155 WRITE(11,*)' INPUT'
0156 WRITE(11,*)
0157 WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
0158 WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0159 WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
0160 WRITE(11,*)' WALL DENSITY IN GM/CUBIC CM = ',RHO2
0161 WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0162 WRITE(11,*)' WALL MATERIAL CONSTANT = ',XL2

0163 WRITE(11,*)
0164 T1T=0.0
0165 T2T=0.0
0166 DO 56 J=1,16
0167 V=FLOAT(J)
0168 CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
0169 & T1,T2,WT,WTCMC)
0169 T1T=T1T+T1*XPV(J)
0170 T2T=T2T+T2*XPV(J)

0171
CONTINUE
T1=T1T
T2=T2T
WT=T1+T2
R12=211.
R22=R21.+T2
R11=R11.+T2+S
R21=R21.+T1+T2+S
VB=4.27*(R21**2.-R11**2.)
VW=4.27*(R22**2.-R12**2.)
WTCMC=RHO1*VB+RHO2*VW
WRITE(II,*)' OUTPUT'
WRITE(II,*)' BUMPER THICKNESS = ',T1,'CM'
WRITE(II,*)' WALL THICKNESS = ',T2,'CM'
WRITE(II,*)' MIN. WEIGHT = ',WT,'CM'
WRITE(II,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
WRITE(II,*)' INPUT'
READ(10,*)D
READ(10,*)RH01
READ(10,*)S
READ(10,*)THETA
READ(10,*)XN
READ(10,*)E1
TIT=0.0
T2T=0.0
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)
CONTINUE
IMPACT5V$MAIN

0229 VB=4.27*(R21**2.-R11**2.)
0230 VW=4.27*(R22**2.-R12**2.)
0231 WTCMC=RHO1*VB+2.81*VW
0232 WRITE(11,*),' OUTPUT'
0233 WRITE(11,*)
0234 WRITE(11,*),' BUMPER THICKNESS = ',T1,' CM'
0235 WRITE(11,*),' WALL THICKNESS = ',T2,' CM'
0236 WRITE(11,*),' MIN. WEIGHT = ',WT,' CM'
0237 WRITE(11,*),' CMC MIN. WEIGHT = ',WTCMC,' KG'
0238 WRITE(11,*)
0239 WRITE(11,*)
0240 GO TO 10
0241 CONTINUE
0242 STOP
0243 END

PROGRAM SECTIONS

Name Bytes Attributes
0 $CODE 4728 PIC CON REL LCL SHR EXE RD NOWRT LONG
1 $DATA 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

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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'
ENDIF

TI:1.93*V**0.18*D**1.91/H**0.91

T2=1.86*T1

CONTINUE

RETURN

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'
ENDIF

TI:1.93*V**0.18*D**1.91/H**0.91

T2=1.86*T1

CONTINUE

RETURN

END
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
TIP=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
   TIP1=0.8*TIP1
   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
   TIP=TIP1
   T2P=T2P1
   WT=WT1
   NP1=NP1+1
   IF(NP1.EQ.100)THEN
      WRITE(11,*) 'NO CONVERGENCE IN PEN4'
      GO TO 557
   ENDIF
   T1P=0.9*T1P1
   T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
   WT1=T1P1+T2P1
   GO TO 590
ENDIF
ELSE
   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

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ENDIF
0060 CONTINUE
0061 D=30.48*D
0062 RHOP=RHOP/1.94
0063 RH01=RH01/1.94
0064 RHO2=RHO2/1.94
0065 T1P=30.48*T1P
0066 T2P=30.48*T2P
0067 IF(T1P/D.LE.0.4)VF=4100
0068 IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069 VF=VF+4000.
0070 IF(V.LE.VF)THEN
0071 WRITE(11,*)' INSIDE OF PEN4 LIMITS'
0072 T1=T1P
0073 T2=T2P
0074 GO TO 1102
0075 ENDIF
0076 CONTINUE
0077 ***** WILKINSON *****
0078 V=V/3280.
0079 T1=0.604*D**2.*RHOP/S
0080 T1=T1*SQR(V/(XL2*RH01*RHO2))
0081 RATIO=D*RHOP/(T1*RHO1)
0082 IF(RATIO.GT.1.0)T2=T1
0083 IF(RATIO.LE.1.0)T2=T1/RATIO
0084 ***** MODIFIED BURCH *****
0085 VB=V*3280.
0086 DB=D/2.54
0087 CM=SQRT(E1/RH01)
0088 CM=CM/30.48
0089 SB=S/2.54
0090 IF(THETA.LE.0.001)GO TO 125
0091 CHI=TAN(THETA)-0.5
0092 F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093 F2=F2+(1.7-12.*T1B/D)*CHI
0094 F3=0.32*(T1B/D)**0.83
0095 F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096 T2F=D*(((F1+0.63*F2)/XN)*(CM/V)**2.29
0097 T2F=T2F*(D/S)**0.71
0098 T2N=F3*(CM/V)**1.33*D/XN
0099 IF(T2N.GE.T2F)T2B=T2N
0100 IF(T2N.LT.T2F)T2B=T2F
0101 T2B=T2B*2.54
0102IF(T2B.GT.T2)NREGION=3
0103 IF(T2B.GT.T2)T2=T2B
0104 GO TO 155
0105 CONTINUE
0106 T1B1=T1/2.54
0107 NITSB=0
0108 XKI=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109 VDELTA=0.0
0110 DELTA3=0.52
0111 DELTA2=2.33*(1.-1.57*DELTA3)
0112 DELTA1=1.33*(2.*DELTA3-1.)
0113 VDELTA1=(1./DELTA1)**DELTA1*(2.8*XKI/(DELTA2*DB**0.57))**DELTA2
0114 VDELTA1=VDELTA1*(1.58*XKI*DB**0.57/DELTA3)**DELTA3
0115 IF(VDELTA1.LT.VDELTA)THEN
0116 DELTA1=1.33*(2.*DELTA3-1.04)
0117 T1B=DELTA1*VDELTA
0118 T2B=VDELTA-T1B
0119 GO TO 499
0120 ENDIF
0121 VDELTA=VDELTA1
0122 DELTA3=DELTA3+0.02
0123 IF(DELTA3.GT.0.063)THEN
0124 T1B=DELTA1*VDELTA
0125 T2B=VDELTA-T1B
0126 GO TO 499
0127 ENDIF
0128 GO TO 1099
0129 499 CONTINUE
0130 ****** COMPARISON OF MODIFIED BURCH AND WILKINSON ******
0131 199 CONTINUE
0132 T10W=T1/2.54
0133 F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134 T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135 T2BT10W=T2BT10W/SB**0.71
0136 T2BT10W=T2BT10W*2.54
0137 RATIOB=(DB*RHOP)/(RHOI*TIB)
0138 T2WT10B=0.364*D**3.0*RHOP*V/(XL2*RH02*S**2.)
0139 IF(RATIOB.GT.1.0)T2WT1OB=T2WT10B*RATIOB
0140 IF(T2BT10W.GT.T2)T2=T2BT10W
0141 T2B=T2B*2.54
0142 IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143 T1B=T1B*2.54
0144 IF(T1B+T2B.LT.TI+T2)THEN
0145 T1=T1B
0146 T2=T2B
0147 ENDIF
0148 155 CONTINUE
0149 1102 IF(T2.LE.0.01)THEN
0150 SIGMA=SY2/144.
0151 T2=3099.1/SIGMA
0152 ENDIF
0153 156 RETURN
0154 END
FUNCTION FT2B(DB,TIB,XN,CM,VB,SB)
F1=2.42*(DB/TIB)**0.33+4.26*(TIB/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

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<th>Bytes</th>
<th>Attributes</th>
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Total Space Allocated 167

ENTRY POINTS

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<td>AP-00000000C0 R*4 XN</td>
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</table>
FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP)

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/RH02)**0.33
XKI=XKI*COS(THETA)

CIPI=(A-B*TIP)/(C+D1*TIP)

IF(CIPI.LE.0.001)THEN
  FT2P=0.0
  GO TO 999
ENDIF

FT2P=XK1*CIPI**0.31
RETURN
END
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

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<th>Bytes</th>
<th>Attributes</th>
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Total Space Allocated: 69

ENTRY POINTS

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<td>AP-00000000C@ R*4 RHOP</td>
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FUNCTIONS AND SUBROUTINES REFERENCED

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<td>R*4 MTH$SQRT</td>
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</table>
SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2, 
T1,T2,WT,WTCMC)

T1=0.604*D**2.*RHOP/S
T1=T1*SQR(T/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
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.O.001)GO TO 425

CHI=TAN(THETA)-0.5
F2=0.5-1.87*(T1B/D)+2.73*(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

CONTINUE

NITSB=0

XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71

VDELTA=0.0

DELTA3=0.52

DELTA2=2.33*(1.-1.57*DELTA3)
DELTA1=1.33*(2.*DELTA3-1.)

VDELTA1=(1./DELTA1)**2.8*XK1/((CM/VB)**2.29/SB**0.71)
VDELTA1*VDELTA1*(1.58*XK1*(DELTA2**0.57))**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

CONTINUE

T1=T1*2.54
T2=T2*2.54
RETURN

END

ORIGINAL PAGE IS OF POOR QUALITY
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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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
2.81 !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
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 = 0.000000E+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 = 0.000000E+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 = 9.793580E-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)
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
   READ(IO,*)D
   READ(IO,*)H
   WRITE(IO,*)'
   WRITE(IO,*)'
   WRITE(IO,*)'
   WRITE(IO,*)'
   WRITE(IO,*)'
   DO 26 J=1,64
      K=J+8
      V=FLOAT(K)
      CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
      T1=T1+T1*XPV(K)
      T2=T2+T2*XPV(K)
   CONTINUE
   T1=T1/3.1335
   T2=T2/3.1335
   WT=WT+T1+T2
   WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
   WTCMC=12.*WTCMC
   WRITE(IO,*)'
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   WRITE(IO,*)'
   WRITE(IO,*)'
   WRITE(IO,*)'
J058   READ(10,*) XN
J059   READ(10,*) E1
J060   WRITE(11,*) ' BOEING'
J061   WRITE(11,*) ' INPUT'
J062   WRITE(11,*) 
J063   WRITE(11,*) 
J064   WRITE(11,*) ' PROJECTILE DIAMETER IN CM = ', D
J065   WRITE(11,*) ' PROJECTILE DENSITY IN GM/CUBIC CM = ', RHOP
J066   WRITE(11,*) ' BUMPER DENSITY IN GM/CUBIC CM = ', RHO1
J067   WRITE(11,*) ' WALL DENSITY IN GM/CUBIC CM = ', RHO2
J068   WRITE(11,*) ' BUMPER/WALL SEPARATION IN CM = ', S
J069   WRITE(11,*) ' WALL MATERIAL CONSTANT = ', XL2
J070   WRITE(11,*) ' BUMPER YIELD STRENGTH IN LB/SQUARE FT = ', SY1
J071   WRITE(11,*) ' WALL YIELD STRENGTH IN LB/SQUARE FT = ', SY2
J072   WRITE(11,*) ' IMPACT ANGLE FROM NORMAL IN DEGREES = ', THETA
J073   WRITE(11,*) ' NUMBER OF PLATES TO PENETRATE AFTER FIRST', '
J074   &
J075   &
J076   &
J077   &
J078   WRITE(11,*) ' BUMPER YOUNGS MODULUS IN GM/CM-SQUARE', 
J079   & ' SEC = ', E1
J080   DO 36 J=1,64
J081   K=J+8
J082   V=FLOAT(K)
J083   CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA, 
J084   & XN,E1,T1,T2,WT,WTCMC)
J085   T1=T1+XPV(K)*T1
J086   T2=T2+XPV(K)*T2
J087   36 CONTINUE
J088   T1=T1/3.1335
J089   T2=T2/3.1335
J090   WT=T1+T2
J091   R12=211.
J092   R22=211.+T2
J093   R11=211.+T2+S
J094   R21=211.+TI+T2+S
J095   VB=4.27*(R21**2.-R11**2.)
J096   VW=4.27*(R22**2.-R12**2.)
J097   WTCMC=RHO1*VB+RHO2*VW
J098   WRITE(11,*) ' OUTPUT'
J099   WRITE(11,*) ' BUMPER THICKNESS = ', T1,' CM'
J100   WRITE(11,*) ' WALL THICKNESS = ', T2,' CM'
J101   WRITE(11,*) ' MIN. WEIGHT = ', WT,' CM'
J102   WRITE(11,*) ' CMC MIN. WEIGHT = ', WTCMC,' KG'
J103   WRITE(11,*) ' MADDEN'
J104   WRITE(11,*) ' INPUT'
J105   WRITE(11,*) 
J106   WRITE(11,*) 
J107   GO TO 10
J108   45 READ(10,*) D
J109   READ(10,*) RHOP
J110   READ(10,*) S
J111   READ(10,*) RHO
J112   WRITE(11,*) ' MADDEN'
J113   WRITE(11,*) ' INPUT'
J114   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
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)
TIT=TIT+T1*XPV(K)
T2T=T2T+T2*XPV(K)
CONTINUE
T1=TIT/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,*), BUMPER THICKNESS = ',T1,'CM'
WRITE(11,*), WALL THICKNESS = ',T2,'CM'
WRITE(11,*), MIN. WEIGHT = ',WT,'CM'
WRITE(11,*), CMC MIN. WEIGHT = ',WTCMC,'KG'
GO TO 10
READ(10,*),D
READ(10,*),RHOP
READ(10,*),RHO1
READ(10,*),RHO2
READ(10,*),S
READ(10,*),XL2
WRITE(11,*), WILKINSON'
WRITE(11,*), INPUT'
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
CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2, T1,T2,WT,WTCMC)

CONTINUE

T1=T1T/3.1335
T2:T2T/3.1335
WT=TI+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,*)' BUMPER THICKNESS = ','TI,'CM'
WRITE(11,*)' WALL THICKNESS = ','T2,'CM'
WRITE(11,*)' MIN. WEIGHT = ','WT,'CM'
WRITE(11,*)' CMC MIN. WEIGHT = ','WTCMC,'KG'

DO 66 J=1,64
K=J+8
V=FLOAT(K)
CALL BURCH(V,D,RHO1,S,THETA, XN,E1,T1,T2,WT,WTCMC)

CONTINUE

T1=T1T/3.1335
T2=T2T/3.1335
```fortran
IMPACT5VM$MAIN

R12 = 2.11
R22 = 2.11 + T2
R11 = 2.11 + T2 + S
R21 = 2.11 + T1 + T2 + S

VB = 4.27 * (R21**2 - R11**2)
VW = 4.27 * (R22**2 - R12**2)
WTCMC = RH01 * VB + 2.81 * VW

WRITE(11,*) 'OUTPUT'
WRITE(11,*)
WRITE(11,*)
WRITE(11,*)
WRITE(11,*)
WRITE(11,*)
WRITE(11,*)
GO TO 10
CONTINUE
STOP
END

BUMPER THICKNESS = ', T1, 'CM
WALL THICKNESS = ', T2, 'CM
MIN. WEIGHT = ', WT, 'CM
CMC MIN. WEIGHT = ', WTCMC, 'KG

PROGRAM SECTIONS

<table>
<thead>
<tr>
<th>Name</th>
<th>Bytes</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
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Total Space Allocated: 6597

ENTRY POINTS

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VARIABLES

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<td>R*4</td>
<td>D</td>
<td>2-000001DC</td>
<td>R*4</td>
<td>E1</td>
<td>2-000001A0</td>
<td>R*4</td>
<td>H</td>
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<tr>
<td>2-00000190</td>
<td>I*4</td>
<td>IV</td>
<td>**</td>
<td>I*4</td>
<td>J</td>
<td>**</td>
<td>I*4</td>
<td>K</td>
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<tr>
<td>2-00000194</td>
<td>I*4</td>
<td>NRUNS</td>
<td>**</td>
<td>R*4</td>
<td>R11</td>
<td>**</td>
<td>R*4</td>
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<td>R22</td>
<td>2-000001C4</td>
<td>R*4</td>
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<td>2-000001CC</td>
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<td>SY1</td>
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<td>2-000001A8</td>
<td>R*4</td>
<td>T1</td>
<td>**</td>
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<td>2-000001AC</td>
<td>R*4</td>
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<tr>
<td>2-000001D4</td>
<td>R*4</td>
<td>THETA</td>
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<td>R*4</td>
<td>V</td>
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<td>R*4</td>
<td>WTCMC</td>
<td>2-000001C8</td>
<td>R*4</td>
<td>XL2</td>
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</table>
```
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
TI=1.93*V**0.18*D**1.91/H**0.91
T2=1.86*T1
CONTINUE
RETURN
END

PROGRAM SECTIONS

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<th>Attributes</th>
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Total Space Allocated | 207

ENTRY POINTS

Address Type Name
0-00000000 NYSMITH

VARIABLES

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<td>R*4</td>
<td>D</td>
</tr>
<tr>
<td>AP-000000014@</td>
<td>R*4</td>
<td>T2</td>
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<th>Type</th>
<th>Name</th>
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<td>R*4</td>
<td>DMAX</td>
</tr>
<tr>
<td>AP-000000004@</td>
<td>R*4</td>
<td>V</td>
</tr>
<tr>
<td>AP-00000018@</td>
<td>R*4</td>
<td>WT</td>
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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
RH01=RH01*1.94
RH02=RH02*1.94
NITSP=0
NITSP=NITSP+1
NP1=0
TIP=T1/30.48
T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP)
WT=TIP+T2P
IF(NITSP.EQ.1)THEN
   T1P1=1.1*TIP
   T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
   WT1=T1P1+T2P1
ENDIF
IF(WT1.GT.WT)THEN
   TIP1=0.82*TIP1
   T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
   WT1=T1P1+T2P1
   IF(WT1.GT.WT)THEN
      GO TO 601
   ELSE
      TIP=TIP1
      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*TIP1
      T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
      WT1=T1P1+T2P1
      GO TO 590
   ENDIF
ELSE
   TIP=TIP1
   T2P=T2P1
   WT=WT1
   T1P1=1.1*TIP1
   T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP1)
   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
END
D = 30.48 * D
RHOP = RHOP / 1.94
RH01 = RH01 / 1.94
RH02 = RH02 / 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.
Ti = 0.604*D**2.*RHOP/S
Ti = Ti*SQR(T(V/(XL2*RH01*RH02))
RATIO = D*RHOP/(T1*RH01)
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 = SQR(T(E1/RH01)
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**2*(F1 + 0.63*F2)/XN*(CM/V)**2.29
T2F = T2F**2*(D/S)**0.71
T2N = F3*(CM/V)**1.33*D/XN
IF(T2N.GE.T2F) T2B = T2N
IF(T2N.LE.T2F) T2B = T2F
T2B = T2B*2.54
IF(T2B.GT.T2) NREGION = 3
GO TO 155
125 CONTINUE
T1B1 = T1/2.54
NITSB = 0
XK1 = (D*B/XN)**1.71* (CM/VB)**2.29/SB**0.71
VDELT A = 0.0
DELTA3 = 0.52
DELTA2 = 2.33*(1. - 1.57*DELTA3)
DELTA1 = 1.33*(2.*DELTA3 - 1.)
VDELT A1 = (1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57)**DELTA2
VDELT A1 = VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
IF(VDELTA1.LE.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

COMPARISON OF MODIFIED BURCH AND WILKINSON *****

T10W=TI/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)/(RHOI*TIB)
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
TIB=TIB*2.54
IF(TIB+T2B.LT.TI+T2)THEN
  TI=TIB
  T2=T2B
ENDIF

IF(T2.LE.0.01)THEN
  SIGMA=SY2/144.
  T2=3099.1/SIGMA
ENDIF
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
FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,TIP)

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*TIP)/(C+D1*TIP)

IF(C1P1.LE.0.001) THEN
  FT2P = 0.0
  GO TO 999
ENDIF

FT2P = XK1*C1P1**0.31
RETURN
END

PROGRAM SECTIONS

<table>
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<tr>
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<th>Bytes</th>
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<td>2 $LOCAL</td>
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Total Space Allocated: 226

ENTRY POINTS

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VARIABLES

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LABELS

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SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
V=V*1.0E05
T1=0.009*SQR(T(V))RHOP*D**2.0
T1=T1/(S*RHO**1.5)
T2=T1
RETURN
END
SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2, 
& T1,T2,WT,WTCMC)

T1=0.604*D**2.*RHOP/S
T1=T1*SQR(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
***** MODIFIED BURCH *****

SUBROUTINE BURCH(V,D,RHOI,S,THETA,XN,E1,TI,T2,WT,WTCMC)

VB=V*3280.
DB=D/2.54
CM=SQRTE1/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*(TIB/D)+(5.*TIB/D-1.6)*CHI**3.0
F2=F2+(1.7-12.*TIB/D)*CHI
F3=0.32*(TIB/D)**0.83
F3=F3+0.48*(TIB/D)**0.33*(SIN(THETA))**3.0
T2F=((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

CONTINUE

NITSB=0
XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
VDELTA=0.0
DELTA3=0.52

DELTAS2=2.33*(1.1-1.57*DELTA3)
DETA1=1.33*(2.*DELTA3-1.)
VDELTA1=1.02*(DELTA1)**2.S*XK1/DELTA2**0.57)**DELTA2
VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3

IF(VDELTA1.LT.VDELTA)THEN
DETA1=1.33*(2.*DELTA3-1.04)
T1=DETA1*VDELTA
T2=VDELTA-T1
GO TO 499

ENDIF
VDELTA=VDELTA1
DELTA3=DETA3+0.02
IF(DETA3.GT.0.63)THEN
T1=DETA1*VDELTA
T2=VDELTA-T1
GO TO 499
ENDIF
GO TO 1099
CONTINUE
T1=T1*2.54
T2=T2*2.54
RETURN
END

VAX FORTRAN