TO: File
FROM: J. H. Ramsthaler
ENCLOSURE: (1) NERVA Program Material

Enclosure (1) represents NERVA Program material philosophy presented in Cleveland on 11 February 1971.

J. H. Ramsthaler, Acting Manager
Product Reliability & Safety Department

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ANSC Program Position

Regarding

Component Design

vs

Materials Plan

Priorities

W. E. Campbell
J. H. Ramsthaler

Presented to SNSO

11 February 1971
ANSC PROGRAM POSITION

ANSC PROGRAM OBJECTIVES

DESIGN LOGIC/RESTRAINTS

EVALUATION OF MATERIALS DATA FOR PROBABILISTIC DESIGN

COMPONENT DESIGN STATUS EXAMPLES

CONCLUSIONS

RECOMMENDATIONS
ANSC PROGRAM OBJECTIVES

SYSTEM DESIGN/ANALYSIS TO DEFINE REQUIREMENTS

CRITICAL COMPONENT DESIGN AND FEASIBILITY DEMONSTRATION

ENHANCE TECHNICAL EXCELLENCE OF CADRE FOR REBIRTH

MAXIMIZE DATA USEABILITY FOR REBIRTH
KEYS TO PROBABILISTIC DESIGN

DEFINED REQUIREMENTS, LOADS, ENVIRONMENTS

CONCEPT BASED ON REQUIREMENTS AND ACHIEVABLE MATERIAL PROPERTIES

DEFINED STRUCTURAL FAILURE CRITERIA

MATERIALS DATA BASED ON DEFINED FAILURE CRITERIA

STRESS DISTRIBUTIONS BASED ON CRITERIA & PART, COMPONENT OR ENGINE TESTS
THE DESIGN/DEVELOPMENT PROCESS

"CONVENTIONAL" PROPERTIES

REQUIREMENTS

SIZING

PRELIMINARY STRUCTURAL ANALYSIS

REJECT CONFIGURATION AND/OR MATERIAL

FMA

FAIR IR CRITERIA DEFINITION

DESIGN ANALYSIS

DESIGN SUPPORT TESTS

STRUCTURAL INTEGRITY VERIFIED PER SAMO C-1

INITIAL PROBABILISTIC EVALUATION

DESIGN 1ST DEVELOPMENT LT

TEST 1ST DEVELOPMENT LT

IDENTIFY MODEL REQUIREMENTS

IDENTIFY FINAL DATA REQUIREMENTS

PRE-QUAL ENGINE DATA

QUAL COMPONENT DATA

RELIABILITY ASSESSMENT

FLIGHT TEST

RELIABILITY ASSESSMENT

IDENTIFY TRUNCATION PROPERTIES

UPDATE MODELS

DEFINITION TRUNCATION PROPERTIES

HIGHER LEVEL TESTS, INCLUDE ENGINE

FINALIZE MODELS

STATISTICAL TESTING

AEROSYSTEM COMPONENT DATA
DESIGN/MATERIALS PLAN OPTIONS

OPTION 1 - ELABORATE MATERIALS DATA NOW

ASSUMES ENVIRONMENT DEFINED

ASSUMES FORM/PROCESS SELECTED

ASSUMES FAILURE CRITERIA KNOWN
  - FMA & PROBABILISTIC MODEL
  - STRUCTURAL ANALYSIS MODEL
  - DESIGN ANALYSIS
  - SUPPORTING ANALYSIS (THERMAL, ETC.)

TENDS TO MAP "ALL" PARAMETERS AT "ALL" ENVIRONMENTS
DESIGN/MATERIALS PLAN OPTIONS

OPTION 2 - DATA DEFERRED, MATCHED TO DESIGN MATURITY

MUST BE ADEQUATE TO SIZE PART

ALLOWS DESIGN TO PROCEED TO FMA/FAILURE CRITERIA

ALLOWS TESTS TO CONFIRM/DEFINE

- LOADS/ENVIRONMENTS
- MODELS/FAILURE CRITERIA

TRUNCATE PARTS ABOVE DESIGN PROPERTIES

DEFINE STATISTICAL CHARACTER FOR KNOWN ENVIR/Criteria
WEIGHT EFFECT OF MATERIAL TEST SAMPLE SIZE

$\bar{S} = 100$ KSI
$V_S = 7\%$
YIELD CRITICAL
SNPO-C-1 MS = 0
$N_S = 10$

% BASE WEIGHT

COST

NUMBER OF DATA SAMPLES, $N_S$

AEROJET NUCLEAR SYSTEMS COMPANY
OBJECTIVES STATISTICAL MATERIALS PROGRAM

- DETERMINE A FEASIBLE DISTRIBUTION OF MATERIALS DATA FOR DESIGN ANALYSIS
- DEVELOP A DISTRIBUTION OF DATA FOR USE IN RELIABILITY ANALYSIS
- ASSURE AT SPECIFIED CONFIDENCE MATERIAL TO BE USED IN ANY ENGINE IS AS GOOD AS VALUES USED IN DESIGN
STATISTICAL ANALYSIS MATERIALS DATA FOR PROBABILISTIC DESIGN

- OBJECTIVES STATISTICAL MATERIALS PROGRAM
- VARIABLES WHICH EXIST IN MATERIALS DATA
- EXPERIENCE TO DATE ANALYZING TEST DATA
- LIMITATIONS OF ANY FINITE ANALYSIS
- EFFECT OF TIME ON ANY BODY OF STATISTICAL DATA
- NECESSITY FOR STATISTICAL ACCEPTANCE TESTING
- RECOMMENDED DATA ACQUISITION PHILOSOPHY
# RECOMMENDED MATERIAL DATA ACQUISITION PROGRAM

<table>
<thead>
<tr>
<th>DESIGN PHASE</th>
<th>PRELIMINARY SIZING</th>
<th>DETAIL DESIGN</th>
<th>COMPONENT DEVELOPMENT TESTING</th>
<th>COMPONENT QUALIFICATION</th>
<th>PRODUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATERIAL OBJECTIVES</td>
<td>LIMITED SCREENING DATA</td>
<td>DATA ON Failure DATA</td>
<td>VENDOR DATA</td>
<td>QUALIFIED VENDORS</td>
<td>GUARANTEE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LOT-TO-LOT DATA</td>
<td>ACCEPTANCE PLAN</td>
<td>MATERIAL MEETS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DATA ON Design CONFIGURATION</td>
<td></td>
<td>TRUNCATION EFFECTS</td>
<td>&quot;R&quot; NEEDS</td>
</tr>
<tr>
<td>VARIABLES IN DISTRIBUTION</td>
<td>WITHIN LOT DATA</td>
<td>WITHIN LOT DATA</td>
<td>WITHIN LOT DATA</td>
<td>ALL FOR QUALIFIED VENDORS</td>
<td>ALL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VENDOR DATA</td>
<td>TEST ERRORS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RISK ASSESSMENT</td>
<td>HIGH K VALUE</td>
<td>HIGH VALUE LOT</td>
<td>DATA FORCES REDESIGN</td>
<td>APPORTIONED RELIABILITY</td>
<td>APPORTIONED RELIABILITY</td>
</tr>
<tr>
<td>EXTREME VALUE LOT</td>
<td>UNKNOWN FAILURE CRITERIA</td>
<td>FAILURE CRITERIA NOT CONFIRMED</td>
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</table>
YIELD STRENGTH
(3 HEATS - CRES 347 SHEETS)

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>SIGMA</th>
<th>99/95 LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>INITIAL DATA BY HEAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>36.6</td>
<td>.71</td>
<td>33.9</td>
</tr>
<tr>
<td>B</td>
<td>35.8</td>
<td>.72</td>
<td>33.1</td>
</tr>
<tr>
<td>C</td>
<td>39.5</td>
<td>.64</td>
<td>37.1</td>
</tr>
<tr>
<td>COMBINED ANALYSIS-TOTAL POPULATION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALL HEATS</td>
<td>37.8</td>
<td>2.33</td>
<td>13.2</td>
</tr>
<tr>
<td>IF HEAT C CAN BE OMITTED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A &amp; B</td>
<td>36.2</td>
<td>1.05</td>
<td>25.1</td>
</tr>
</tbody>
</table>

AEROJET NUCLEAR SYSTEMS COMPANY
### Room Temperature

**Circumferential Yield Strength**

(3 Forgings - CRES 347)

<table>
<thead>
<tr>
<th>Forging</th>
<th>Mean</th>
<th>Sigma</th>
<th>99/95 Limit</th>
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</thead>
<tbody>
<tr>
<td>021</td>
<td>36.0</td>
<td>1.06</td>
<td>32.0</td>
</tr>
<tr>
<td>027</td>
<td>33.3</td>
<td>1.04</td>
<td>28.7</td>
</tr>
<tr>
<td>033</td>
<td>29.8</td>
<td>0.88</td>
<td>26.5</td>
</tr>
<tr>
<td>All Forgings</td>
<td>33.0</td>
<td>3.25</td>
<td>0</td>
</tr>
<tr>
<td>027 &amp; 033</td>
<td>31.7</td>
<td>2.97</td>
<td>1.3</td>
</tr>
<tr>
<td>033 + Part 027</td>
<td>30.4</td>
<td>1.32</td>
<td>22.8</td>
</tr>
<tr>
<td>033 + Part 027</td>
<td>29.8</td>
<td>1.15</td>
<td>25.6</td>
</tr>
</tbody>
</table>
EFFECT METHOD OF ANALYSIS ON 99/95 POINT

LOT 2 LOT 1 LOT n
VENDOR B VENDOR A VENDOR M
- OPTIONS -

STATISTICAL ANALYSIS OF MATERIALS DATA

● TREAT ALL DATA AS SINGLE POPULATION
  ASSUMES -
  ● NO VENDOR/LOT/HEAT DIFFERENCES
  ● SPECIMEN-TO-SPECIMEN VARIATIONS SAME AT ALL CONDITIONS

● ALLOW FOR VENDOR DIFFERENCES
  INCLUDE VENDOR VARIATIONS IN MATERIAL DISTRIBUTION
  ASSUMES -
  ● RANDOM VENDOR SAMPLE FROM LARGE POPULATION
  ● WITHIN VENDOR VARIATIONS SAME FOR ALL VENDORS
  OR -
  PERFORM SEPARATE ANALYSIS FOR EACH VENDOR
  ASSUMES -
  ● NO LOT/HEAT DIFFERENCES WITHIN VENDOR

● ALLOW FOR LOT DIFFERENCES WITHIN VENDORS
  INCLUDE LOT AND VENDOR VARIATION IN MATERIAL DISTRIBUTION
  ASSUMES -
  ● RANDOM SAMPLE OF VENDORS AND LOTS WITHIN VENDORS
  ● LOT-TO-LOT VARIATIONS UNIFORM OVER VENDORS
  ● WITHIN LOT VARIATIONS UNIFORM OVER ALL LOTS OVER ALL VENDORS
  OR
  PERFORM SEPARATE ANALYSIS FOR EACH LOT
PRODUCT VARIABILITY

BASIC MATERIAL VARIABILITY
1. NON HOMOGENEITY WITHIN A LOT
2. VARIATIONS BETWEEN LOTS
3. VENDOR VARIATIONS
4. SHAPE PURCHASED IN

FABRICATION & PROCESSING
1. DESIGN EFFECTS - SHAPE, ETC.
2. PROCESSING EFFECTS - ROLLING FORGING CASTING
3. WITHIN VENDOR VARIATIONS
4. VENDOR TO VENDOR VARIATIONS

TECHNICAL ERRORS
1. NON-REPRODUCIBLE TEST CONDITIONS
2. VARIABILITY WITHIN A PIECE OF TEST EQUIPMENT
3. TEST EQUIPMENT VARIATIONS
4. OPERATOR DIFFERENCES AND ERRORS
5. MEASUREMENT AND DATA PROCESSING UNCERTAINTIES

TIME EFFECTS
1. ANY OF ABOVE COULD CHANGE WITH TIME
EFFECT OF TIME ON MATERIALS PROPERTIES

HIGH

STRENGTH

TIME

LOW

VENDOR A

VENDOR B

AEROJET NUCLEAR SYSTEMS COMPANY
CONCLUSIONS

• IT IS NOT PRACTICAL NOR TECHNICALLY SOUND TO DEVELOP A UNIVERSAL DISTRIBUTION OF MATERIALS DATA AT ANY POINT IN A PROGRAM

• ANY DISTRIBUTION DEVELOPED SHOULD BE SPECIFIC FOR THE APPLICATION INTENDED

• ACCEPTANCE TESTS SHOULD BE DESIGNED TO ASSURE THE DISTRIBUTION USED IN RELIABILITY ANALYSIS IS OBTAINED IN EACH ENGINE

• IT IS NOT WISE TO DEVELOP EXTENSIVE MATERIALS TEST DATA EARLY IN A DESIGN EFFORT BECAUSE OF VENDOR CHANGES, DESIGN CHANGES, AND UNKNOWN ACCEPTANCE TEST PROCEDURES

• MATERIALS DATA SHOULD BE OBTAINED IN AN ORDERLY MANNER AS A PROGRAM PROGRESSES TO MEET DESIGN RELIABILITY NEEDS
WEIGHT EFFECT OF STRESS VARIABILITY

\[ S = 100 \text{ KSI} \]
\[ V_S = 7\% \]

YIELD CRITICAL
SNPO-C-1 MS = 0
\[ N_S = 10 \]

\[ % \text{ BASE WEIGHT} \]

\[ \text{STRESS VARIABILITY, } V_S - \% \text{ OF MEAN} \]

AEROJET NUCLEAR SYSTEMS COMPANY
NOZZLE/PRESSURE VESSEL FLANGE

\[ \bar{s} = 26 \text{ KSI} \quad \bar{s} = 31 \text{ KSI} \quad \bar{s} = 36 \text{ KSI} \quad \bar{s} = 44 \text{ KSI} \quad \bar{s} = 46 \text{ KSI} \]

\[ V_s = 0.03 \quad V_s = 0.03 \quad V_s = 0.04 \quad V_s \approx 0.03 \]

3.0 FLANGE
2.5 FLANGE
347 MATERIAL
2.0 FLANGE
ARMCO MATERIAL

AEROGJE NUCLEAR SYSTEMS COMPANY
# Nozzle Design Data Requirements

<table>
<thead>
<tr>
<th>ARMCO Jacket</th>
<th>Forged Tensile - Forward Flange, Convergent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forged/Welded Tensile - Aft Torus</td>
</tr>
<tr>
<td></td>
<td>Thermal Expansion - Temperature Range</td>
</tr>
<tr>
<td></td>
<td>Thermal Conductivity - Temperature Range</td>
</tr>
<tr>
<td></td>
<td>Forged Fracture Toughness - Aft Torus</td>
</tr>
<tr>
<td></td>
<td>E Modulus</td>
</tr>
<tr>
<td></td>
<td>Forged Stress Corrosion</td>
</tr>
<tr>
<td></td>
<td>Tensile Irradiated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>347 Tubes</th>
<th>Tube Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tube Low Cycle Fatigue</td>
</tr>
<tr>
<td></td>
<td>Tube Tensile Irradiated</td>
</tr>
</tbody>
</table>

© Aerojet Nuclear Systems Company
NOZZLE TUBE THERMAL FATIGUE

\[ \bar{\sigma} = 0.0237 \ (60 \text{ CYCLE STRAIN}) \quad \bar{\sigma} = 0.0272 \ (60 \text{ CYCLE STRAIN}) \]

(ESTIMATED BY MANSON/COFFIN METHOD)

\[ V_s = 0.17 \quad V_s = 0.09 \]

TESTS TO DEFINE ALLOWABLE MEAN STRAIN
PRESSURE VESSEL MID CYLINDER

$\bar{s} = 37 \text{ KSI}$  \hspace{1cm}  $\bar{s} = 49 \text{ KSI}$  \hspace{1cm}  $\bar{s} = 53 \text{ KSI}$

$V_s = 0.01$  \hspace{1cm}  $V_s = 0.04$

$135^\circ\text{F WALL TEMP}$  \hspace{1cm}  $-5^\circ\text{F WALL TEMP}$

MATERIAL = 7075-T73
<table>
<thead>
<tr>
<th>Material</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>7075 Cylinder</td>
<td>FORGED ( K_{IC} )</td>
</tr>
<tr>
<td></td>
<td>FORGED ( K_1 )</td>
</tr>
<tr>
<td></td>
<td>FORGED TENSILE IRRADIATED</td>
</tr>
<tr>
<td></td>
<td>FORGED ( K_{IC} ) IRRADIATED</td>
</tr>
<tr>
<td></td>
<td>FORGED STRESS CORROSION, SHORT TRANSVERSE</td>
</tr>
</tbody>
</table>
PRESSURE VESSEL CLOSURE BOLT

\[ s = 180 \text{ KSI} \quad \bar{s} = 210 \text{ KSI} \]

REDESIGN FOR
MS \geq 0

\[ V_S = 0.04 \]
\[ V_S = 0.03 \]
\[ V_S = 0.04 \]
TURBINE INLET HOUSING

STRESS/LOAD CORRELATION

$S = 100 \text{ KSI}$

$S = 174 \text{ KSI}$

$V_S = .07$

$V_S = .02$

A286 718-

TO BE ESTABLISHED BY COMPONENT TEST

AEROJET NUCLEAR SYSTEMS COMPANY
SECOND TURBINE ROTOR DISC FAILURE GOVERNING STRESS (BORE)
TITANIUM

\[ s = 49 \text{ KSI} \quad V_s = 0.03 \]

\[ S = 149 \text{ KSI} \quad V_S = 0.024 \]
### Fracture Mechanics Approach to Disc Stresses

<table>
<thead>
<tr>
<th></th>
<th>1st Impeller</th>
<th>1st Turbine Rotor</th>
<th>2nd Turbine Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Allowable Duty Cycle Ratio</strong></td>
<td>$\frac{8400}{60} = 140.0$</td>
<td>$\frac{1800}{60} = 30.0$</td>
<td>$\frac{1470}{60} = 24.5$</td>
</tr>
<tr>
<td><strong>Critical Size FLaw Ratio</strong></td>
<td>$\frac{.980}{.048} = 20.4$</td>
<td>$\frac{.501}{.048} = 10.4$</td>
<td>$\frac{.441}{.048} = 9.2$</td>
</tr>
<tr>
<td><strong>Fracture Strength Calculated Stress Ratio</strong></td>
<td>$\frac{316,000}{46,000} = 6.9$</td>
<td>$\frac{228,000}{46,500} = 4.9$</td>
<td>$\frac{226,000}{48,600} = 4.7$</td>
</tr>
</tbody>
</table>

* * Calculated Fracture Strength $> F_{tu}$; Strength truncated to $F_{ty}$ for analysis
SECOND TURBINE ROTOR DISC BURST SPEED
(CONVENTIONAL DUCTILE ANALYSIS)
TITANIUM

\[ N_0 = 26,910 \text{ RPM} \]

\[ V_S = 0.005 \]

\[ V_S = 0.038 \]

\[ N_b = 49,800 \text{ RPM} \]
TURBINE BLADE FATIGUE

TO BE TESTED

$\bar{s} = 3\text{ KSI}$

$\bar{s} = 1.6\text{ KSI}$

$\bar{s} = 3.3\text{ KSI}$

$n = 7 \times 10^8 \text{ CYCLES}$

$V_s = .03$

$\bar{s} = 48\text{ KSI}$

$\bar{s} = 60\text{ KSI}$

$V_s = .05$

$V_s = .05$

NERVA PREDICTION

NOTCHED FRACTURE TOUGHNESS SPECIMEN

PRELIMINARY SIZING CRITERIA

ANTICIPATED BLADE RESULT

SMOOTHED FLAT FATIGUE SPECIMEN

AEROJET NUCLEAR SYSTEMS COMPANY
PUMP ROTOR RETENTION BOLT

718

\[ \bar{s} = 89 \text{ KSI} \]

\[ \bar{s} = 149 \text{ KSI} \]

\[ \bar{s} = 215 \text{ KSI} \]

\[ \bar{s} = 218 \text{ KSI} \]

\[ V_s = 0.075 \]

\[ V_s = 0.07 \]

\[ V_s = 0.05 \]

\[ K_f = 0.65 \]

\[ K_f = 2.0 \]

ESTABLISH FRICTION LOAD
BY COMPONENT TEST

A286

AEROJET NUCLEAR SYSTEMS COMPANY
## TURBOPUMP DESIGN DATA REQUIREMENTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Property</th>
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<tbody>
<tr>
<td>310 HOUSINGS</td>
<td>FATIGUE</td>
</tr>
<tr>
<td></td>
<td>WELDED TENSILE</td>
</tr>
<tr>
<td></td>
<td>THERMAL EXPANSION</td>
</tr>
<tr>
<td></td>
<td>THERMAL CONDUCTIVITY</td>
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<tr>
<td>Titanium Discs</td>
<td>FRACTURE TOUGHNESS</td>
</tr>
<tr>
<td>Titanium Blades</td>
<td>FATIGUE</td>
</tr>
<tr>
<td>Bearing Cages</td>
<td>HOOP TENSILE</td>
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<tr>
<td></td>
<td>HOOP TENSILE IRRADIATED</td>
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<tr>
<td>Barium Orifice Rings</td>
<td>THERMAL EXPANSION</td>
</tr>
<tr>
<td>A286 Tie Bolts</td>
<td>TENSILE</td>
</tr>
<tr>
<td></td>
<td>THERMAL EXPANSION</td>
</tr>
</tbody>
</table>
VALVE/ACTION DESIGN DATA REQUIREMENTS

9310 GEARS

NOTCHED TENSILE

K_i

TENSILE IRRADIATED

K_{IC} IRRADIATED

BRONZE SEALS

NOTCHED TENSILE

BERYLLIUM COPPER SPRINGS

TENSILE

TENSILE IRRADIATED

K_{IC} IRRADIATED

A286 SPRINGS

DYNAMIC MODULUS

TENSILE

FEURALON CAGES

TENSILE IRRADIATED

FLEXURE IRRADIATED

TITANIUM BODY

K_i
CONCLUSIONS

RELATIVELY SMALL ADDITIONAL DATA REQUIREMENT FOR DESIGN TO PROCEED

ADDED DESIGN MATURITY REQUIRED TO DEFINE DATA REQUIREMENTS

TRUNCATION APPROACH AFFORDS REASONABLE DESIGN RISK

STATISTICAL DATA DEFERRAL IS PROPER
RECOMMENDATIONS

SELECT DESIGN PROPERTIES TO REACH FLAT PART OF CURVE
INTERPRETATION OF AVAILABLE DATA
TEST TO SAMPLE SIZE OF 10, WITHIN LOT ONLY
ASSESS TRUNCATION SCRAP RISK

TEST FOR FAILURE CRITERIA CHARACTERISTICS DEFINED BY ANALYSIS/TEST
TEST TO SAMPLE SIZE OF 10

TRUNCATE DEVELOPMENT PARTS TO ABOVE VALVES

STATISTICAL TEST TO FINAL FORM/ENVIRON/CRITERIA

ADJUST TRUNCATION LIMITS IF COST EFFECTIVE

ASSESS RELIABILITY