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PLANNING DEVELOPMENT: AN
EVOLUTIONARY APPROACH USING
RELIABILITY ENGINEERING AS A TOOL   Unclas
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Inspection Planning Development: An evolutionary Approach

Using Reliability Engineering as a Tool

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SUMMARY AND CONCLUSION

This paper proposes an evolutionary approach for inspection planning which introduces various reliability engineering tools into the process and assess system trade-offs among reliability, engineering requirement, manufacturing capability and inspection cost to establish an optimal inspection plan. The examples presented in the paper illustrate some advantages and benefits of the new approach. Through the analysis, reliability and engineering impacts due to manufacturing process capability and inspection uncertainty are clearly understood; the most cost effective and efficient inspection plan can be established and associated risks are well controlled; some inspection reductions and relaxations are well justified; and design feedbacks and changes may be initiated from the analysis conclusion to further enhance reliability and reduce cost. The approach is particularly promising as global competitions and customer quality improvement expectations are rapidly increasing.

1. INTRODUCTION

Traditionally, people establish an inspection plan on a product unit according to blue print requirements. Quality planning engineers assess the criticality of the inspection features, largely dependent upon their experience and "best guess, judgment call", then flow down the inspection requirements including the inspection items and levels to inspectors. Generally in the practice, components or system reliability and concerned failure modes were not extensively analyzed, and inspection cost and feasibility were not emphasized and manufacturing process capability was not considered during the inspection planning process. Consequently, much of the inspection effort and cost might have been wasted on insignificant inspection features or on in-efficient and in-effective inspections. On the other hand, some critical features may not receive proper attention, and possibly escape the inspection, resulting in a jeopardized reliability. It is also often seen that the communications between quality planning engineering and design engineering are very weak. Even when they communicate, quantitative data from one organization is not necessarily utilized by the other.

To be cost-effective and to achieve a high reliability, we must develop an alternative approach. Some analytical tools must be utilized and system engineering approaches adopted to overcome the weakness and the drawbacks of the traditional inspection planning methodology. This paper illustrates how various reliability engineering tools and statistical methods can be utilized which not only helps to realize cost and reliability objectives but promotes concurrent engineering as well.

2.TRADITIONAL INSPECTION PLANNING METHODOLOGY

Products are generally complex, especially from the defense and aerospace industry. Manufacturing processes and steps of making them are divided among many different departments. It is observed that many inspections are performed by inspectors who don't have a complete understanding of the product's function, the impact of the inspection feature on product reliability, and fitness for use. Customer requirement on traceability and necessary standardization of inspection process also require development of a formal inspection planning document. Usually, this task is accomplished by a quality planning engineer with the resultant inspection planning document flowed to inspectors for guidelines and instructional use.

During the past several years, the Space Shuttle Main Engine (SSME) program developed a formal classification of characteristics ("c of c") process to support inspection planning. The "c of c" utilizes Failure Mode and Effect Analysis (FMEA) and Critical Item List (CIL) as a baseline to assign one of three levels of classifications (critical, primary and major) to an inspection feature. FMEA/CIL describes the component functions, failure scenario and design retention rational, assesses in details design life, fracture mechanics, material properties, factors of safety, and evaluates the consequence of non-conformance. Based upon the FMEA/CIL, the "c of c" allows a quality planning engineer to include essential design information and all reliability concerns into the inspection planning document. All reliability-sensitive characteristics are identified, significant inspection requirements are established, and effective allocation of inspection resource and

effort are facilitated.

Though the "c of c" work has significantly employed failure mode analysis information, the process still lacks quantitative analysis to determine inspection levels and inspection sample size. The traditional sampling inspection standards, such as MIL-STD-105 (Sampling Procedures and Tables For Inspection by Attributes) and MIL-STD-414 (Sampling Procedures and Tables For Inspection by Variables) presented Acceptable Quality Level (AQL) concept as well as consumer's risk and producer's risk, but in reality, these statistics were hardly correlated to the end product reliability in decision making. Product design parameter profiles and engineering data base were seldom quantitatively utilized by quality planning engineers. The manufacturing capability and quality level were generally not considered in the inspection planning. All these facts motivate us to develop a systematic, analytical approach for inspection planning, which utilizes and integrates all information and data from engineering analysis, failure mode analysis, manufacturing capability study and inspection uncertainties to establish an optimal inspection plan.

3.PROPOSED EVOLUTIONARY APPROACH

Reliability engineering and statistical methods provide essential tools to evolve the current inspection planning practice to a more systematic and analytical approach. FMEA/CIL analysis has enumerated failure modes and failure consequences. The fault tree analysis is utilized to clearly define the failure path of a component non-conformance. Statistical process control and manufacturing process capability studies provide data on the inspection feature

quality level and manufacturing stability. An inspection sampling plan characterizes itself in terms of probability of acceptance relative to an incoming lot quality. Probabilistic analysis modeling of a system or a sub-system allows us to connect all data and information together and integrate them into a system model. Computer simulations will then be employed to assess the trade-offs and sensitivities quantitatively for different input including engineering and reliability requirements, manufacturing capabilities and sampling inspection plans. An optimal inspection plan can be selected from the simulation result, according to the specific engineering and reliability requirement, manufacturing capability and inspection trade-offs and cost considerations.

Flow Chart 1 illustrates the proposed approach. Flow Chart 2 describes the detailed steps of the approach.

Flow Chart 1

An Evolutionary Approach of Inspection Planning

DATA

| FMEA/CIL REQUIREMENT | KEY PROCESS CHAR. MFG CAPABILITY | ENGINEERING DESIGN REQUIREMENT | RELIABILITY |

TECHNIQUES

FAULT TREE ANALYSIS - CLEARLY DEFINE FAILURE PATH

PROBABILITY DIST. - QUANTIFY VARIATIONS & UNCERTAINTIES

SIMULATION - QUANTITATIVELY INTEGRATE AND ANALYZE THE DATA

INSPECTION REQUIREMENT

AQL, OC CURVES ANCHORED

SAMPLING PLAN FORMULATED

MONITORING PLAN ESTABLISHED

Flow Chart 2
INSPECTION PLANNING FLOW CHART
RELIABILITY AND COST DRIVEN APPROACH

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                    ┌──────────────────────┐
                    │   ENGINEERING AND    │
                    │     RELIABILITY      │
                    │    REQUIREMENTS      │
                    └──────────┬───────────┘
                               │
┌──────────┐                   ▼                  ┌──────────────────┐
│ PRODUCT  │         ┌──────────────────────┐     │  MANUFACTURING   │
│  FMEA    │────────▶│  ENGINEERING ANALYSIS│◀────│      FMEA        │
└──────────┘         │  OR FAULT TREE       │     └──────────────────┘
┌──────────┐         │      ANALYSIS        │     ┌──────────────────┐
│ DRAWINGS │────────▶│                      │◀────│   INSPECTION     │
└──────────┘         └──────────┬───────────┘     │    FEATURES      │
                                │                  └──────────────────┘
        ┌──────────────────┐    │    ┌──────────────────────┐
        │ FAILURE HISTORY  │    │    │   MANUFACTURING      │
        │ (LESSONS LEARNED)│    │    │  CAPABILITY DATA     │
        └────────┬─────────┘    │    └──────────┬───────────┘
                 │              ▼               │
                 └──────────────┬───────────────┘
                    ┌───────────▼──────────────┐
                    │  SYSTEM OR COMPONENT     │
                    │  REQUIREMENT DEFINITION  │
                    │     (REL., COST  ETC.)   │
                    └───────────┬──────────────┘
                                ▼
                    ┌──────────────────────────┐
                    │   TRADE OFF ANALYSIS     │
                    │  (COMPUTER MODEL         │
                    │     OR OTHERS)           │
                    └───────────┬──────────────┘
                                ▼
                    ┌──────────────────────────┐
                    │   INSPECTION PLAN        │
                    │   ESTABLISHMENT          │
                    └───────────┬──────────────┘
                                ▼
                    ┌──────────────────────────┐
                    │     MONITORING           │
                    │        PLAN              │
                    └──────────────────────────┘
```

4. ILLUSTRATIVE EXAMPLES

Example 1: Tube wall thickness sampling inspection plan development

There are 1080 tubes in a particular component of SSME. The drawing tolerance for the tube wall thickness of a specific location is .0065"+.0027"/.0000. The tubes are manufactured by a supplier of the company. This example tries to answer the following questions: During the acceptance of the product, do we need to perform 100% inspection to check the wall thickness ? If we do sampling inspection, what is the proper sample size to guarantee reliability ?
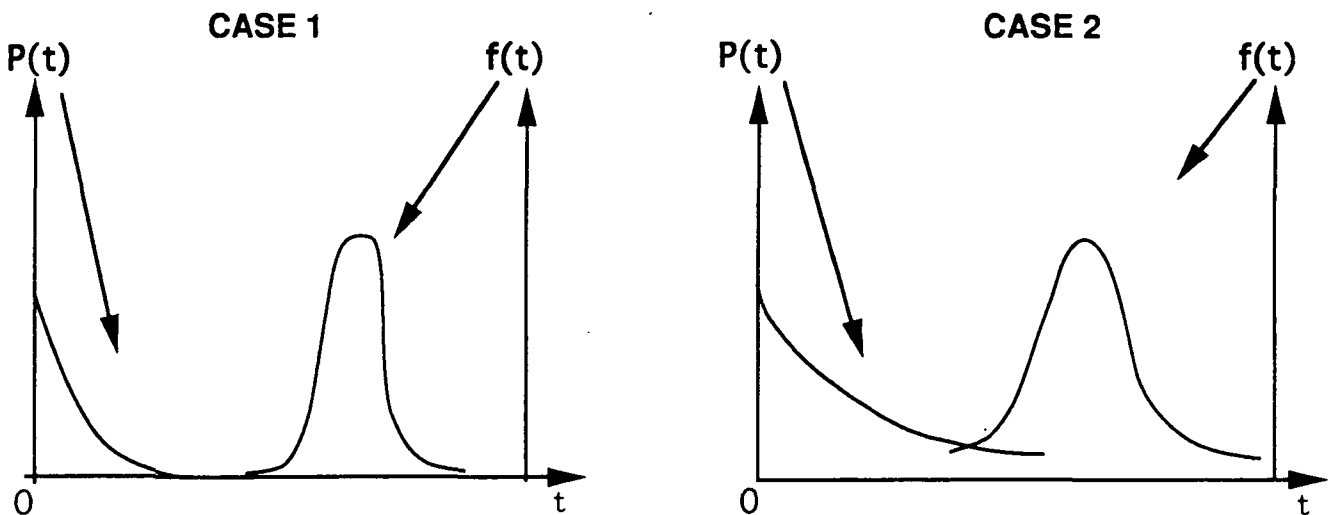
Failure Mode and Effect Analysis

Through the FMEA/CIL study, it is determined that tube leaking is the failure mode of concern. The leakage causes loss of SSME fuel, resulting in off-nominal engine operating condition. The worst case from multiple tube ruptures and leakages will drive turbine discharge temperature to exceed engine redline limit, therefore, prematurely shutting down the engine.

If tube walls are too thin, they will cause tubes failure during proof pressure test or during engine hot fire test. If tube walls are too thick, they may result in restricted coolant flow, which will accelerate degradation of the walls and eventually cause tubes to crack and leak. For simplicity and illustrative purpose, we are just studying thinner wall effect and the corresponding inspection strategy and scheme in this example.

Engineering Structural Analysis

Assume p(t) is the structural failure probability curve as function of wall thickness t. The f(t) is wall thickness distribution density function. We compare the following two cases:

Since the overlapping area under the p(t) curve and the f(t) curve for the case 2 is much bigger than for the case 1, it is obvious that the inspection for the case 2 should be much more stringent than the inspection for the case 1 in order to screen out the tubes which may potentially cause failure.

The structural failure probability curve p(t) is roughly estimated to be

$$p(t) = \exp(-1523 * t) , \qquad t > 0$$

Manufacturing Capability Assessment

It has been determined that the tube wall thickness is normally distributed. But due to manufacturing lot-to-lot variation, both mean m and standard deviation s of the distribution are random variables. From data, it is estimated that m is roughly subject to an uniform distribution which is bounded by .0070" and .0086" and s is roughly subject to another uniform distribution which is bounded by .0005" and .0010".

Reliability Requirement

We require the failure probability of any incoming lot of tubes installed on engine after passing inspection, be less than .00005 with 95% confidence level.

Computer Simulation Model

```
                        │
          ┌─────────────▼──────────────┐
          │ Estimate p(t) and m, s distributions │
          └─────────────┬──────────────┘
             ┌──────────▼──────────┐
             │ Choose a sampling plan to start │
             └──────────┬──────────┘
             ┌──────────▼──────────┐
             │ Specify total simulation number N │
             └──────────┬──────────┘
```

Estimate p(t) and m, s distributions

Choose a sampling plan to start

Specify total simulation number N

Simulate N times yet? — Y → Does the S.P. meet req't ? — Y →

N ↓

Generate an (m, s) pair

Generate sample from (m, s) distributions and compute estimated m and s

Use the MIL-STD-414 S.P. to screen the sample

Does the sample pass the sampling inspection?

Y ↓   N ↓

Counting good lots and bad lots   Counting good lots and bad lots

Choose another S.P. to run the model again

stop, use the S.P. for the future inspection

repeat simulations

The Simulation Result

Input into the simulation model:

$p(t) = \exp(- 1523 * t)$;

$f(t)$ = normal distribution with mean m and standard deviation s, where

m is a random variable with Uniform (.0070, .0086) and

s is a random variable with Uniform (.0005, .0010)

Sampling plan: MIL-STD-414 Single specification limit, normal inspection sampling plan with sample size 5.

Output: the Graph 1 shows the simulation result, which indicates the simulated confidence levels as function of different acceptable quality levels representing different sampling plans. The result tells us for this particular application, the sampling plan with AQL
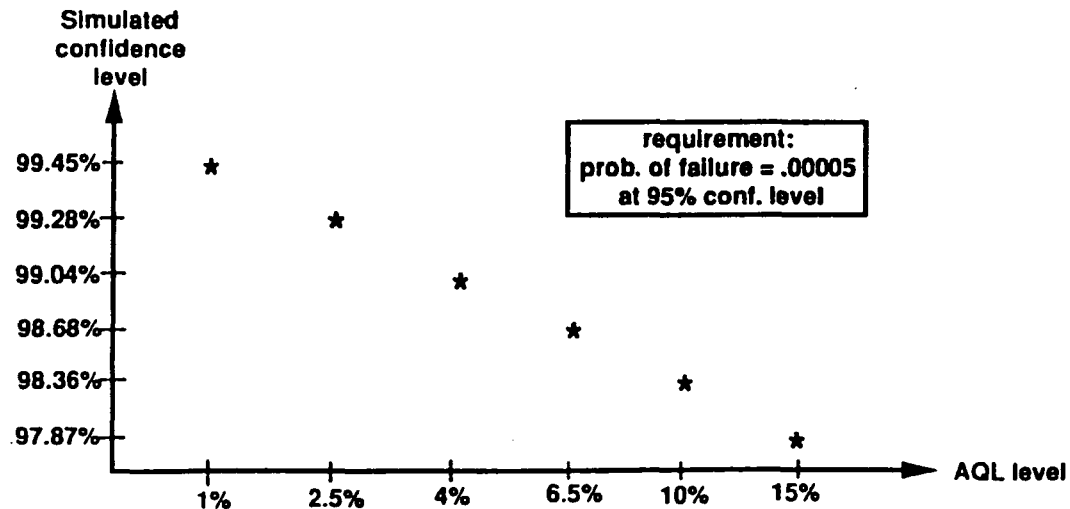
15% is good enough to meet the reliability requirement.

<u>Graph 1</u>

<u>Wall Thickness Inspection</u>

<u>Result from the Computer Simulation Model</u>

Input information: choose the single specification limit, normal inspection sampling plan, code letter "D" (sample size 5) from MIL-STD-414 Table B-1. Manufacturing capability: m ~ Uniform(.0070, .0086); s ~ Uniform(.0005, .0010).

Simulated
confidence
level

| requirement: |
| prob. of failure = .00005 |
| at 95% conf. level |

99.45% ★

99.28%   ★

99.04%   ★

98.68%   ★

98.36%   ★

.97.87%   ★

AQL level

1%   2.5%   4%   6.5%   10%   15%

<u>Sensitivity Study</u>

Now we assume a manufacturing process of another vendor is worse than the previous one. The wall thickness distribution has more variability. The standard deviation s of the density f(t) is subject to a wider Uniform distribution:

s is Uniform (.0007, .0013) instead of Uniform (.0005, 0010).

We run the simulation again. It is seen from the comparison graph, Graph 2, for the worse manufacturing process, we have to apply a more stringent sampling plan which has AQL 1% in order to screen out the bad parts and protect reliability.

Graph 2

Tube Wall Thickness Inspection

Comparison Results for Different Manufacturing Capabilities

Input information: choose the single specification limit, normal inspection sampling plan, code letter "D" (sample size 5) from MIL-STD-414 Table B-1.

Simulated
confidence
level

req't: prob. of failure = .00005 at 95% conf. level
★ is from mfg. cap.: m ~ Uniform(.0070, .0086)
s ~ Uniform(.0005, .0010)
o is from mfg. cap.: m ~ Uniform(.0070, .0086)
s ~ Uniform(.0007, .0013)

99.45%
99.28%
99.04%
98.68%
98.36%
97.87%

95.46%
93.98%
92.45%
90.56%
88.57%
86.18%

AQL level

1%   2.5%   4%   6.5%   10%   15%

Example 2: Fuel sleeve hole diameter inspection

There are 120 sleeve elements in an SSME component. Every element has 168 sleeve holes on it which allow engine fuel to flow through and mix uniformly with liquid oxygen to form hot gas. The sleeve elements are supplied by a vendor who manufactures the sleeve holes using electro-discharge machining process. The drawing tolerance for hole is .018"+.002/-.000. In the past the vendor was requested to 100% inspect the hole diameters. But the inspection process was lengthy and costly. In this example, we study the impact of sleeve hole diameters on engine performance and investigate the possibility of reducing inspection without jeopardizing reliability.

Failure Mode and Effect Analysis

There are two failure modes associated with the hole dimension

non-conformance. The first one is non-uniformity of the hot gas flow
which may cause local off-nominal mixture of fuel with oxygen and
result in local component erosion. Because of the design nature, the
local erosion, if occurring, is self-limiting. The second failure
mode is reduced or increased fuel flow resulted from undersized or
oversized hole diameters. The consequence of this failure mode is to
generate an engine system off-nominal condition, which may
potentially cause engine sub-system temperatures to exceed redline
limit, therefore prematurely shutting down the engine.

Engineering Aerothermo-dynamics Analysis

Aerothermo-dynamics engineering analysis was performed to assess
the impact and sensitivity of different hole diameters on engine flow
balancing. The corresponding engine sub-system flow rates and
temperature changes for the different hole diameters are calculated
and summarized in Table 1.

Table 1. Aerothermo Property of Different Hole Sizes

(Drawing tolerance .018"+.002/-.000)

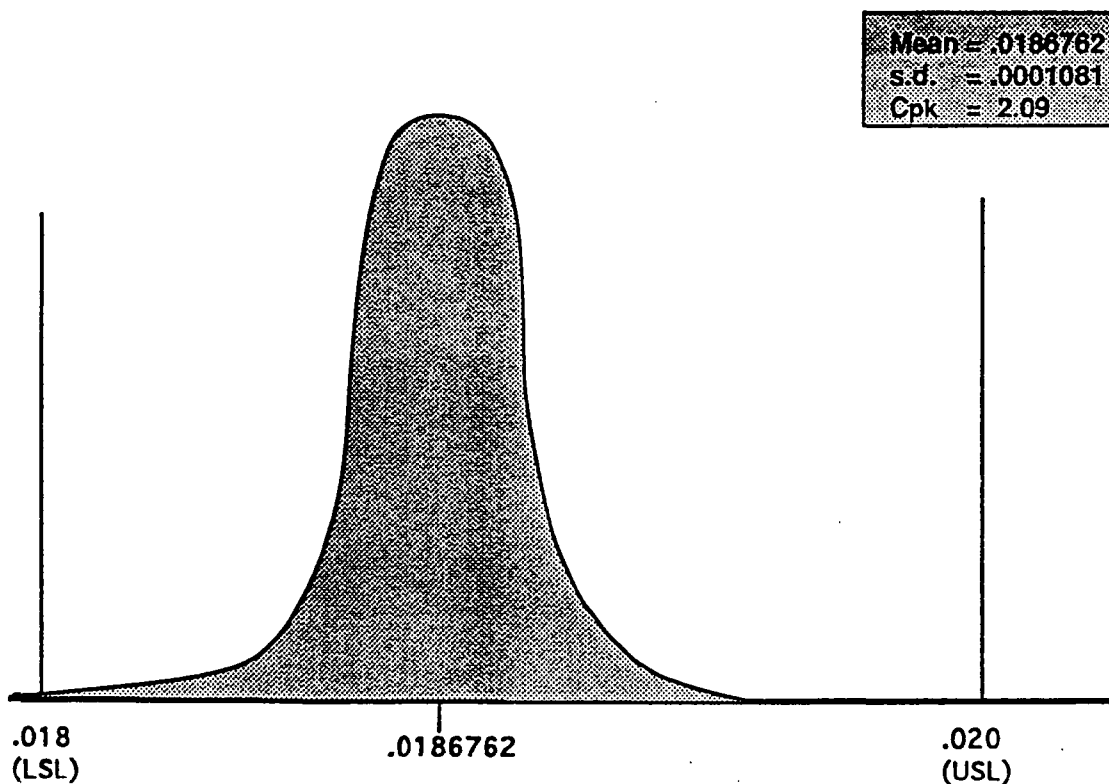| All Sleeve Holes Sized to	Sub-system 1 Temp. Delta	Sub-system 2 Temp. Delta	Sub-system 3 Flow Rate Delta
.014	-34R	+52R	.11 lbs/sec.
.016	-15R	+22R	.05
.018	0	0	0
.020	+13R	-17R	-.04
.022	+23R	-31R	-.07
.024	+32R	-42R	-.10
.026	+39R	-51R	-.13

Manufacturing Process Capability Assessment

The sleeves are manufactured utilizing the electro-discharge machining process. The vendor uses 7 electrodes to fabricate holes on each of 7 rows respectively. Each electrode is used 12 times and then cut and trimmed to a new wire electrode portion to account for the tool wear. After studying the vendor's manufacturing process, it was determined that the process is stable and capable of meeting the drawing requirement. A set of sleeve hole data was collected and plotted in Graph 3.

Graph 3

Fuel Sleeve Hole Manufacturing Capability

(Drawing Tolerance .0018"+.002/.000)

Mean = .0186762
s.d. = .0001081
Cpk = 2.09

.018
(LSL)   .0186762   .020
                                                          (USL)
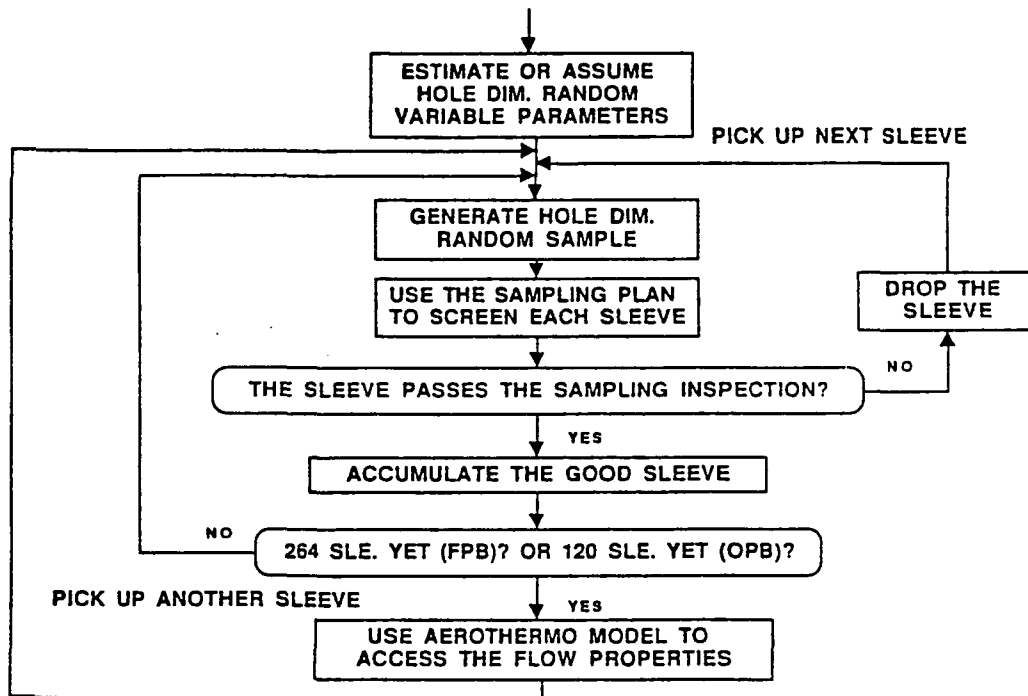
Reliability and System Performance Requirement

We require that the sub-system 1 temperature change be less than +/-6.5R, the sub-system 2 temperature change be less than +/-8.5R and the sub-system 3 flow rate change within +/-.02 lb/second. These requirements provide enough safety margin to prevent engine operation condition from exceeding redline limits.

Computer Simulation Model

Taking all the data and information into consideration, we integrate them into a computer simulation model, which allows us to quantitatively assess the impact of the hole dimensions and effect of sampling plans.

Fuel Sleeve Hole Diameter Inspection Plan

Computer Simulation Model

```
                    ↓
        ┌──────────────────────────┐
        │  ESTIMATE OR ASSUME      │
        │  HOLE DIM. RANDOM        │
        │  VARIABLE PARAMETERS     │        PICK UP NEXT SLEEVE
        └──────────────────────────┘
                    │
        ┌──────────────────────────┐
        │  GENERATE HOLE DIM.      │
        │  RANDOM SAMPLE           │
        └──────────────────────────┘
                    │
        ┌──────────────────────────┐          ┌──────────────┐
        │  USE THE SAMPLING PLAN   │          │  DROP THE    │
        │  TO SCREEN EACH SLEEVE   │          │  SLEEVE      │
        └──────────────────────────┘          └──────────────┘
                    │                                NO
        ( THE SLEEVE PASSES THE SAMPLING INSPECTION? )──────┘
                    │ YES
        ┌──────────────────────────┐
        │  ACCUMULATE THE GOOD SLEEVE │
        └──────────────────────────┘
                    │
   NO   ( 264 SLE. YET (FPB)? OR 120 SLE. YET (OPB)? )
        │
   PICK UP ANOTHER SLEEVE          │ YES
        ┌──────────────────────────┐
        │  USE AEROTHERMO MODEL TO │
        │  ACCESS THE FLOW PROPERTIES │
        └──────────────────────────┘
```

Proposed Sampling Plan

1. Inspect 5 holes among 24 of each row, total 35 holes on every sleeve.

2. If one or more inspected hole diameters are out-of-print, reject that sleeve.

3. If two or more sleeves are rejected, stop manufacturing and initiate corrective actions.

The Simulation Result

Table 2 summarizes the simulation result. It reveals that for a manufacturing process capability with mean .0185" and standard deviation .0001", the sleeves which pass the proposed inspection provide adequate engine flow property as follows: Sub-system 1 temperature change within 3.4R compared with the requirement +/-6.5R; Sub-system 2 temperature change within 3.54R versus the requirement +/-8.5R; and Sub-system 3 flow rate change within -.01 lb/second versus the requirement +/-.02 lb/sec.. It also shows that when the manufacturing process degrades, the sampling plan will detect the trend and reject the parts very easily, therefor triggering actions to correct manufacturing problems. For example, for a manufacturing capability with mean .0185" and standard deviation .0003", the sampling plan rejects 83% of the submitted sleeves. Overall evaluation of engineering analysis and simulation result suggests that a relaxation of the drawing tolerance from .018"+.002/-.000 to .018"+/-.002 is reasonable and will further reduce manufacturing cost.

Table 2: Sleeve Hole Inspection Simulation Result

hole dia.mean \ hole dia. s.d.		.0001"			.0002"			.0003"		
		simu ave	simu max	sleeve rej.rate	simu ave	simu max	sleeve rej.rate	simu ave	simu max	sleeve rej.rate
.0183"	Sub-Sys 1 Temp. Delta	1.94	2.10	6%	1.96	2.21	93%	1.83	1.83	99.9%
	Sub-Sys 2 Temp. Delta	-2.01	-2.19	6%	-1.99	-2.35	93%	-1.67	-1.67	99.9%
	Sub-Sys 3 flow rate Delta	-.01	-.01	6%	-.01	-.01	93%	-.01	-.01	99.9%
.0185"	Sub-Sys 1 Temp. Delta	3.24	3.40	0.0%	3.24	3.55	22%	3.27	3.65	83%
	Sub-Sys 2 Temp. Delta	-3.36	-3.54	0.0%	-3.35	-3.71	22%	-3.33	-3.87	83%
	Sub-Sys 3 flow rate Delta	-.01	-.01	0.0%	-.01	-.01	22%	-.01	-.01	83%

Acknowledgment

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Biographies

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Mr. Graf has over 20 years experience in aerospace engineering, manufacturing and quality assurance. He has held various positions in reliability and quality engineering management, project management and procurement quality assurance. His current position is Associate Quality Manager of Flight Support Team in Space Shuttle Main Engine (SSME) program at Rocketdyne Division of Rockwell International. He oversees SSME quality and reliability policies and activities. Mr. Graf is a graduate of California State University at Northridge.

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Mr. Huang is a reliability engineer supporting the Space Shuttle Main Engine (SSME) program at the Rocketdyne Division of Rockwell International. He is currently involved in SSME reliability analyses and various quality engineering activities. He obtained a Manufacturing Engineering Certificate from UCLA in 1991. He received a B.S. in Computational Mathematics in 1982 from Shanghai University of Science and Technology, an M.A. in Mathematics in 1986 from Temple University and an M.S. in Statistics in 1987 from Iowa State University. Mr. Huang is a member of ASQC and is ASQC Certified Quality Engineer and Certified Reliability Engineer.