11. TCM AIRCRAFT PISTON ENGINE EMISSION REDUCTION PROGRAM*

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INTRODUCTION

Teledyne Continental Motors is currently under contract with the National Aeronautics and Space Administration to establish and demonstrate the technology necessary to safely reduce general aviation piston engine exhaust emissions to meet the EPA 1980 Emission Standards with minimum adverse effects on cost, weight, fuel economy, and performance. The contract is intended to (1) provide a screening and assessment of promising emission reduction concepts, and (2) provide for the preliminary design and development of those concepts mutually agreed upon. These concepts will then go through final design, fabrication, and integration with a prototype engine(s). Verification testing will then be performed at our facility.

Teledyne Continental Motors has completed the first portion (task II) of the NASA contract (NAS3-19755): "Screening and Assessment Analysis and Selection of Three Emission Reduction Concepts." A technical report is being prepared and is expected to be published during the last quarter of 1976 (ref. CR-135074).

A systems analysis study and a decision making procedure were used by TCM to evaluate, trade off, and rank the candidate concepts from a list of 14 alternatives. Cost, emissions, and 13 other design criteria considerations were defined and traded off against each candidate concept to establish its merit and emission reduction usefulness. A computer program documented in NASA TN X-53992 was used to aid the evaluators in making the final choice of three concepts.

The following is a summary of the Task II study.

APPROACH

The objectives of Task II were to conduct a screening analysis on a

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*NASA Contract NAS3-19755.

minimum of ten promising concepts and select three for further development. The approach used to fulfill the objectives was fivefold:

(1) Select a preliminary list of concepts

(2) Conduct a detailed literature search

(3) Contact firms for additional data

(4) Define criteria and method of evaluation

(5) Rank concepts based on a consistent set of weighted cost-effectiveness criteria

The first three steps of the approach resulted in a list of fourteen concepts which were investigated during the remainder of Task II. The promising concepts are listed in order of general category:

- Stratified charge combustion chambers:
  - Honda compound vortex controlled combustion
  - Texaco controlled combustion system
  - Ford programmed combustion
- Improved cooling combustion chamber
- Diesel combustion chambers:
  - 4-stroke, open chamber
  - 2-stroke, McCulloch
- Variable camshaft timing
- Improved fuel injection system
- Ultrasonic fuel atomization - Autotronics
- Thermal fuel vaporization - Ethyl TFS
- Ignition systems:
  - Multiple spark discharge
  - Variable timing
- Hydrogen enrichment
- Air injection

Step four of the approach was accomplished by selecting and defining the decision factors (criteria). The criteria chosen in the evaluation of the concepts were as follows:

Cost	Integration
Reliability	Producibility
Safety	Fuel economy
Technology	Weight and size
Performance	Maintainability and maintenance
Cooling	Emissions
Adaptability	Operational characteristics
Materials	

Each decision factor was further defined by listing specific questions which were used in evaluating each concept.

The ranking of the concepts, step (5), was accomplished with a computer program that helps a decision maker to make consistent decisions under conditions of both certainty and uncertainty. The model aids in obtaining consistent rankings of the decision criteria and of the concepts relative to each of the criteria. The emphasis coefficients assigned to each criteria, the merit scores assigned to each concept relative to each criteria, and the associated uncertainties determined the overall merit coefficient for each concept. These merit coefficients defined the concept ranking which was used as a guide in the final selection of three concepts.

EMISSION RESULTS

Through the detailed literature search and contact with firms considered expert in their respective field, raw emissions data at the specific aircraft modal conditions were acquired for many of the concepts. These raw emissions data were input to the TCM aircraft cycle emissions deck. Where adequate raw emissions data were not available, concepts were evaluated by analyzing their impact on emissions as applied to the IO-520-D engine. The IO-520-D engine operating at the lean fuel flow limit of the model specification (case 1) was chosen as representative of a high volume production engine.

Figure 11-1 represents the emission levels for the concepts evaluated using raw emissions data. Shown for reference are the emission levels for the IO-520-D engine and two automotive engines, a conventional high production Chevrolet 350 CID V-8 engine and a high performance BMW 123 CID I-4 engine. The Chevrolet engine was a 1975 model without a catalytic converter, exhaust gas recirculation, or secondary air injection. The BMW engine was a 1973 model lacking the same pollution control devices. Neither engine met the EPA aircraft emission standard. While CO and HC were within the limits, the oxides of nitrogen were well over the allowable emissions as compared to 30 percent of the allowable emissions for the IO-520-D engine.

Graphical representation of engine emissions versus time-weighted fuel-air equivalence ratio from figure 11-1 and four current production TCM engines resulted in the generalized curves presented in figure 11-2. Data from the four TCM engines, IO-520-D, GTSIO-520-K, O-200-A, and Tiara 6-285-B, operating at three mixture strength schedules were utilized in developing the rich end of the curves. Emissions from all open-chamber-4-stroke Otto cycle engines evaluated adhered very closely to these trends. Note that only a narrow band of 7-mode time-weighted equivalence ratios, 1.03 to 1.13, exists where all three regulated pollutants are at or below the EPA limits.

The specific emission reduction conclusions for each concept are now presented.

Honda Compound Vortex Controlled Combustion (CVCC)

Raw emission data, received for the Honda CVCC, were based on operation with the standard exhaust system. The exhaust manifold was designed with an inner liner to increase exhaust gas residence time and provide an intake manifold "hot spot." Some benefits of HC and CO oxidation and thermal fuel vaporization are therefore inherent in the data. Honda CVCC met all EPA emission standards and was the best stratified charge concept evaluated on overall emission reduction (see table 11-1).

Ford Programmed Combustion (PROCO)

Ford PROCO emission data indicated high oxides of nitrogen emissions (32 percent over EPA limit) at a relatively lean 0.5 time-weighted equivalence ratio. Hydrocarbons and carbon monoxide, at less than 10 percent of the EPA standard, were typical of lean operation (fig. 11-1).

Texaco Controlled Combustion Systems (TCCS)

Three sets of raw emission data were evaluated on the TCM aircraft cycle emissions deck. Almost all resulting time-weighted equivalence ratios were the same. In two cases the engines were operated on gasoline while the third case used diesel fuel. Oxides of nitrogen emissions were comparable for all three cases and exceeded EPA limits up to 38 percent. Carbon monoxide emissions were below the standard but not as consistent as NO_x or CO, varying from 12 to 58 percent of the EPA limit (fig. 11-1).

Improved Cooling Combustion Chambers

No raw emissions data were available for evaluating an improved cooling combustion chamber. Exhaust emission levels were projected by realizing that improved cooling during climb and takeoff will permit leaner fuel-air ratios while maintaining engine power. Application of this theory to IO-520-D data resulted in emission levels of 106, 95, and 44 percent of the EPA standard for CO, HC, and NO_x, respectively. These levels reflect a 16 percent CO decrease and a 47 percent NO_x increase. Hydrocarbons were not significantly reduced since climb and takeoff contribute only a small amount of the total HC emissions for the overall cycle.

McCulloch Two-Stroke Diesel

Raw emissions data for this concept were evaluated on the TCM aircraft cycle emissions deck. The resulting emission levels were 10, 140, and 54 percent of the EPA standard for CO, HC, and NO_x, respectively. These HC and NO_x levels compare to 47 and 163 percent of the EPA standard, respectively, for a conventional four-stroke open chamber diesel (table 11-1). The low NO_x level results from the unique combustion chamber and piston design and the fuel-air mixture burning/quenching process. This quenching process may also account for the high hydrocarbons. It should be noted that the HC level is conservative since full power data were not available and the rated power was reduced accordingly. Hydrocarbons should decrease for the higher speed/load conditions.

Four-Stroke Open Chamber Diesel

Raw data from three four-stroke open chamber diesels were evaluated on the TCM aircraft cycle emission deck. Data from one engine, a Datsun, is suspect due to the extremely low NO_x emissions (fig. 11-1). Oxides of nitrogen for the other two cases exceeded EPA limits by up to 90 percent. This level resulted from the high peak temperatures normally associated with diesel engines. Carbon monoxide and HC were below EPA standards for all cases.

Variable Camshaft Timing

Emission predictions for variable camshaft timing were based on Tiara 6-285-B engine data for idle, taxi, and approach modes, and on IO-520-D case 1 data for climb and takeoff modes. Tiara data were considered representative of HC emissions that could be expected on the IO-520-D for low valve overlap in low speed modes. This is due to higher engine speeds of a geared engine in these modes and because of the comparatively low Tiara valve overlap. The Tiara emission data was taken at IO-520-D fuel-air ratios for the respective modes and corrected for flow rate differences. No exhaust emission reduction benefits from exhaust gas recirculation were assumed for the IO-520-D because the design point for valve overlap is at high engine speed; that is, large valve overlap already exists on the IO-520-D and no increase in internal exhaust gas recirculation would be expected from variable camshaft timing Consistent with the literature, the CO remained essentially unchanged, exceeding the EPA limit by 27 percent. Hydrocarbons were reduced by 49 percent of the EPA standard (from 97 to 48 percent) relative to the IO-520-D engine. Oxides of nitrogen emissions remained essentially unchanged at 33 percent of the EPA standard.

Improved Fuel Injection System

Projected emission levels for an improved fuel injection system were determined by evaluating a system which would alleviate the attendant operational problems associated with carbureted or conventional aircraft fuel injection systems. That is, the system must provide a better homogeneous fuel-air mixture and decrease cylinder to cylinder fuel-air ratio variations. It was further required that the system would be compensated to maintain lean fuel-air ratios within a reasonable band regardless of the air density. The actual range of fuel-air ratios that could be maintained was defined as a time-weighted equivalence ratio range of 1.03 to 1.13. Exhaust emission reductions were based on the IO-520-D engine (fig. 11-3), resulting in absolute emission levels of 55, 90, and 58 percent of the EPA standard for HC, CO, and NO_x, respectively.

Ultrasonic Fuel Atomization

No raw emission data were obtained for this concept. It was assumed to have the same emission reduction potential as the thermal fuel vaporization concept. This approach was taken because both concepts have essentially the same end result, homogeneous fuel-air mixture with decreased cylinder to cylinder fuel-air ratio variation.

Thermal Fuel Vaporization - Ethyl TFS

Raw emissions data from two engines, an American 350 CID V-8 and a European four cylinder I-4 were obtained and evaluated on the TCM aircraft emissions cycle deck. The results were inconsistent for the two engines (fig. 11-1). Results for the American V-8 seemed more reasonable because of the predictable insignificant effect on NO_x, whereas for the European engine the NO_x was reduced by almost 60 percent. The results of the American V-8 data analysis were used. Hydrocarbons were reduced 39 percent (with the addition of the turbulent flow system) with insignificant effects on CO and NO_x.

Variable Timing Ignition System

Variable timing ignition will not significantly reduce exhaust emissions for the aircraft emission cycle. However, the ability to provide variable ignition at idle, taxi, and the approach modes will decrease the acceleration problem associated with leaning these modes. Projected emission reductions of 11 percent for HC, 8 percent for CO, and an increase of 17 percent for NO_x based on IO-520-D data resulted in absolute CO, HC, and NO_x emission levels of 116, 86, and 35 percent of EPA standards, respectively. These levels were predicated on variable timing ignition improving transient operation at idle, taxi, and approach modes. The quantity of improvement was defined as that required to alleviate acceleration problems at the richest fuel-air ratio at which transient problems were encountered during lean-out testing on an uninstalled engine. This method resulted in fuel-air ratios richer than existing safety limits but leaner than best power fuel-air ratios (case 1) for the previous modes. Best power fuel-air ratios were used for climb and takeoff modes. The resulting exhaust emissions are considered conservative because at the fuel-air ratios chosen only transient hesitation was noted rather than complete response failure. Variable timing ignition should easily provide at least the minimum improvement required for satisfactory transient operation at the previous conditions.

Multiple Spark Discharge Ignition System

Multiple spark discharge ignition systems provide a leaner misfire limit than do the conventional ignition systems. No emission reduction capability was demonstrated in the literature over a sizable range of fuel-air ratios except for hydrocarbons which differed beyond the point of incipient misfire. For the purpose of ranking a multiple spark discharge ignition, based on emission reduction potential, this theory was adhered to, that is, emissions would not be affected for a given fuel-air ratio above the lean limit of a conventional system. The IO-520-D engine case 1 emission levels were assumed to be the standard (table 11-1).

Hydrogen Enrichment System

No raw data were available for determining the exhaust emission reduction potential for an aircraft piston engine using the hydrogen enrichment method. The Jet Propulsion Laboratory predicted emission characteristics on an opposed aircraft engine using hydrogen enrichment. The predictions were based on the assumption that the correlations of indicated specific emission production with equivalence ratio are valid. The data base used in generating these representations at richer equivalence ratios ($\geq$1.1) was for a TCM IO-520-D engine. Data for ultra-lean operation were obtained by JPL for a 350 CID V-8 engine operating with both straight gasoline and mixtures of gasoline and hydrogen-rich gases from a hydrogen generator. Reasonable coalescence occurred where the data sets joined.

Idle, taxi, and approach modal indicated specific emission rates (lbm pollutant/indicated horsepower hr) were defined at 0.6 equivalence ratio. The corresponding values of indicated horsepower were calculated from known brake horsepower and friction horsepower characteristics for the IO-520-D engine. Hydrogen enrichment was assumed nonoperational during takeoff and climb so that engine power could be maintained. Emission levels for takeoff and climb were taken directly from IO-520-D data for case 1. Applying hydrogen enrichment to the IO-520-D resulted in CO, HC, and NO_x levels of 68, 43, and 30 percent of the EPA standards, respectively (table 11-1).

Air Injection

The exhaust emission reduction potential of secondary air injection was evaluated using data from a TCM O-200 engine. The results of that analysis were converted into terms that express the change in each pollutant per quantity of air injected as a function of equivalence ratio. These effects were applied to an IO-520-D engine, case 1 emission data with the appropriate time-weighted equivalence ratio, assuming an air injection flow rate equal to 20 percent of the engine inlet air flow rate. Twenty percent was selected on the basis of minimum air injection flow rate necessary to meet EPA emission standards for all three pollutants at reasonable pump size and power requirements.

Expected reductions of 33 percent for HC, 23 percent for CO, and an increase of 13 percent for NO_x were projected resulting in absolute levels for HC, CO, and NO_x of 65, 97, and 34 percent of the EPA standards, respectively.

CRITERIA DEVELOPMENT AND METHOD OF EVALUATION

The selection of cost and design emission reduction criteria was made after extensive documentation review and internal discussion. Furthermore, the criteria (defined as "decision factors") are traceable to the NASA Request for Proposal (LeRC RFP No. 3-499786Q). A list of solution attributes (indicating a further breakdown of policy, monetary, and technical issues pertinent to the criteria) was generated and used for evaluating the merit and usefulness of emission reduction concepts. A solution attribute is defined as a subset of knowledge, considerations, and thoughts (sometimes intangible or ill-defined) that identifies, particularizes, or supplements the meaning of the criteria. Solution attributes actually drive the definition of criteria elements. Sample listings of the attributes for cost and safety are shown in figures 11-4 and 11-5.

Four evaluators were asked to make critical value judgments concerning the relative importance of the criteria as they would be used to assign merit to the emission reduction alternative concepts. A combined total of 42 years of industrial experience in combustion analysis, equipment design, reciprocating and turbine engine development, and systems engineering is noted for the evaluation team.

Each evaluator reviewed the criteria and the associated attributes. He was then asked to choose between criteria elements as to their relative importance. For example, given any pairwise combination of criteria elements, which one is preferred? Are the cost criteria more important than the emissions criteria? Figure 11-6 shows the process used by each evaluator. The criteria choices were denoted by rows and columns. Criteria comparison choices were numerically recorded in each cell for the attending row and column. By distributing a value (whose interval lies between [0,1]) among criteria i^{th}, criteria j^{th}, and the associated uncertainty ij^{th}, the evaluator logically orders the criteria to emphasize its importance to him. Thus, the following equation below illustrates a formal statement of the value assignment procedure between any pair of properties and the associated uncertainty:

$$\text{Relative importance of property } j = 1 - \begin{bmatrix}\text{Relative} \\ \text{importance} \\ \text{of property } i\end{bmatrix} - \begin{bmatrix}\text{Associated} \\ \text{uncertainty} \\ \text{of property } ij\end{bmatrix}$$

Property i^{th} value assignment is recorded in the upper left portion of the matrix cell, property j^{th} value assignment is calculated as the compliment of the matrix cell, and the associated uncertainty between the properties is recorded in the lower right portion of the cell as shown in figure 11-6. Hence, by substituting arbitrary values for cost, reliability, and the associated uncertainty, it follows that

$$\begin{aligned}\text{Reliability } (j) &= 1 - \text{Cost } (i) - \text{Uncertainty } (ij) \\ &= 1 - 0.6 - 0.1 \\ &= 1 - 0.7 \\ &= 0.3\end{aligned}$$

were the specific values assigned according to figure 11-6. A total of 105 pairwise choices was made. A simple logic check, based on the theory of transitivity, was made on the evaluator's choices to ensure consistent pairwise value judgments. Once the evaluator's value judgments were assigned and consistency established, a second computer program was used to rank his multidimensional complex criteria set. The criteria ranking emphasis coefficient is based on the theory of combinations as used to normalize the relative importance and uncertainty scores. An emphasis coefficient is associated with each criteria element and it is defined as the sum of the importance scores for that element normalized by the total number of pairwise comparisons made.

A similar analysis was conducted for evaluating each concept relative to each criteria element. Figure 11-7 shows the process used by each evaluator. That is, given the choice among alternative concepts, when traded off against the criteria, which ones are preferred? Is the improved cooling combustion chamber concept preferred over the air injection concept when considering emission benefits, advantages, and disadvantages? These are the fundamental questions answered by each evaluator. The choice among pairwise solution alternatives were depicted numerically. By distributing a value among alternative i^{th}, alternative j^{th}, and the associated uncertainty ij^{th}, the evaluator logically ordered the concepts to emphasize the importance to him. A total of 1365 pairwise choices (91 decisions for each of the 15 criteria elements) were made by each evaluator. Again, a consistency check was made to ensure a logical ordering of the evaluator's preferences. A second program that calculates the evaluator's merit scores (associated with his comparison of concepts and criteria elements) was enabled after consistency was established. The procedure for ranking the alternative concepts is similar to that of the criteria, as explained previously. The calculation of the merit coefficient for each concept is simply a summation of the product of criteria emphasis coefficients and the concept merit scores. The merit coefficient yields the resultant ranking. An example of a concept comparison trade-off evaluation for one of the evaluators is shown in figure 11-8.

CONCEPT RANKING AND SELECTION OF THREE CONCEPTS

After each evaluator established his individual criteria set and design concept preference ranking (and associated merit scores), he was directed to meet with his colleagues and select an optimized criteria and concept data set that reflects the consensus of the group. This was accomplished by arguing in favor of a generalized or explicit interpretation of the attributes/criteria elements, amalgamating ideas, compromising individual differences, and forming an opinion that was tolerated by the evaluation group. The optimized criteria data set was selected first and then the group assembled an optimized concept data set. The data flow process is schematically shown in figure 11-9.

The optimized emission reduction criteria ranking is shown in figure 11-10. Inspection of figure 11-10 shows that emissions, performance, and fuel economy rank within the top 40 percentile of 15 criteria elements. Emissions is ranked first; performance, third; and fuel economy, sixth. The previous criteria elements are considered congruent with respect to the decision criterion since they are explicitly stated in the primary and secondary objectives as the needs to be satisfied. Safety (ranked second), cooling (fourth), and weight and size (fifth) are important criteria design considerations that are also included in the upper 40 percentile. The first seven criteria elements are considered the dominant requirements that have the greatest influence on the selection of solution alternatives.

Table 11-1 depicts a final listing of the ordering for the fourteen concepts evaluated on the basis of emission usefulness. Table 11-2 presents a correlation matrix that depicts the results of the concept versus criteria tradeoff rank and merit scores as the result of the evaluators combined value judgments. The concepts are listed in order of their final ranking for the optimized preference analysis. The numbers shown at each intersection point represent the order of concept ranking based on the merit scores when compared with the criteria element. The improved cooling combustion chamber design concept is ranked first because it scored well among the dominant criteria elements - that is, first for safety, cooling, and weight and size, and moderately well among the remaining four dominant criteria. The improved cooling combustion chamber ranked ninth with the emissions criteria, but the influence of the remaining dominant criteria elements forced this design concept to be the top ranked candidate.

The improved fuel injection systems and air injection design concepts are ranked second and third, respectively. Inspection of dominant criteria (see table 11-2) shows a relative high rank scoring for these two candidates when compared against the remainder of design concepts. It becomes apparent that the further one proceeds down the list of design concepts the corresponding numerical ranking values increase in magnitude for the criteria elements, thus indicating lower utility.

Based on the results of the concept-criteria trade-off analysis, the following three concepts have been approved by NASA/Lewis Research Center for further development:

Improved fuel injection system

Improved cooling combustion chamber

Air injection

DISCUSSION

Q - W. Houtman: What would your selection have been if the hydrocarbon and NO_x requirements were removed?

A - B. Rezy: If CO was the only pollutant being considered, the emissions ranking would change significantly. The diesel concept has the lowest CO emissions; however, the influence of the remaining criteria has been shown to have a great effect on the overall ranking. As stated earlier, the hydrogen enrichment concept best satisfied the emission criteria; however, it ranked eighth in the overall preference analysis. Therefore, I cannot make a statement as to how the overall preference analysis would change if only CO was considered. We will, however, report these findings[1] as part of the proceedings from this symposium.

Q - G. Kittredge: Could you tell me whether the PROCO and TCCS stratified charge engines that you showed were versions that employed catalysts and exhaust gas recirculation?

A - B. Rezy: They did not.

Q - H. Gold: When you say improved fuel injection system, what kind of improvements do you have in mind?

A - B. Rezy: An improved fuel injection system will consist of a timed, airflow sensitive system capable of supplying fuel at moderate pressure to the injectors. A timed, moderate fuel pressure system is required to ensure a fuel mist with adequate cylinder distribution as opposed to the present continuous flow, low pressure system. An airflow (or speed-density) sensitive system is required to maintain the desired fuel-air ratio, which will control the emission levels, and, togehter with proper cylinder distribution, will provide better engine transient response. We are currently evaluating a servo-mechanical controlled system and an electronically controlled system.

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[1]Comment on findings by B. Rezy following the Symposium: Table 11-3 presents the emission ranking for each concept based on the EPA standards for CO only. Referring to table 11-1 reveals the significant differences in the two rankings. The overall preference analysis based on changing only the emission criteria is shown in table 11-4. Due to the strong effect of the remaining criteria the four top tanking concepts did not significantly change. Air injection did decrease from third to fourth position since the emission ranking for this concept changed considerably when only CO was considered. However, the three concepts selected for further evaluation would not change if only CO was considered as the emission criteria.

CONCEPT RANKING FOR EMISSIONS

RANK	CONCEPT	PERCENT EPA STANDARDS		
		CO	HC	NOx
1	HYDROGEN ENRICHMENT, JPL	68.	43.	30.
2	HONDA CVCC	36.	22.	76.
3	IMPROVED FUEL INJECTION SYSTEMS	90.	55.	58.
4	AIR INJECTION	97.	65.	34.
5	TEXACO CCS	8.	58.	128.
6	FORD PROCO	4.	7.	132.
7	2-STROKE DIESEL, McCULLOCH	10.	140.	54.
8	4-STROKE DIESEL, OPEN CHAMBER	3.	47.	163.
9	IMPROVED COOLING COMBUSTION CHAMBER	106.	95.	44.
10	VARIABLE CAMSHAFT TIMING	127.	48.	33.
11	THERMAL FUEL VAPORIZATION, ETHYL	126.	59.	30.
12	ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	126.	59.	30.
13	VARIABLE TIMING SYSTEM	116.	86.	35.
14	MULTIPLE SPARK DISCHARGE SYSTEM	126.	97.	30.
**************				
REF.	IO–520–D, CASE 1	126.	97.	30.

TABLE 11-2

CONCEPT RANK ORDERING VERSUS CRITERIA IMPORTANCE

CONCEPT	CRITERIA														
	DOMINANT							SECONDARY				MINOR			
	EMISSIONS	SAFETY	PERFORMANCE	COOLING	WEIGHT AND SIZE	FUEL ECONOMY	COST	RELIABILITY	TECHNOLOGY	OPERATIONAL CHARACTERISTICS	MAINTAINABILITY AND MAINTENANCE	INTEGRATION	MATERIALS	PRODUCIBILITY	ADAPTABILITY
IMPROVED COOLING COMBUSTION CHAMBER	9	1	6	1	1	6	6	3	2	1	1	6	3	2	4
IMPROVED FUEL INJECTION SYSTEMS	3	2	1	14	2	5	7	4	1	6	2	4	2	7	6
AIR INJECTION	4	5	8	9	6	14	1	5	3	3	5	2	6	1	1
MULTIPLE SPARK DISCHARGE SYSTEM	14	3	5	7	3	12	2	6	4	2	3	1	1	5	2
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	12	4	9	11	5	10	4	1	5	5	4	10	4	4	7
VARIABLE TIMING IGNITION SYSTEM	13	6	3	8	4	11	5	7	7	9	6	3	5	6	3
THERMAL FUEL VAPORIZATION, ETHYL	11	7	10	13	7	9	3	2	6	4	7	9	7	3	5
HYDROGEN ENRICHMENT, JPL	1	14	7	4	8	1	12	8	9	12	8	7	14	8	8
TEXACO CCS	5	8	12	2	10	2	10	12	13	10	13	11	13	11	11
2-STROKE DIESEL, McCULLOCH	7	11	2	6	13	4	13	9	11	13	9	13	12	13	14
FORD PROCO	6	9	13	3	11	3	9	11	14	11	14	12	9	12	12
VARIABLE CAMSHAFT TIMING	10	13	4	10	9	13	8	14	8	8	10	5	8	9	9
HONDA CVCC	2	12	11	12	12	8	11	13	10	7	11	8	10	10	10
4-STROKE DIESEL, OPEN CHAMBER	8	10	14	5	14	7	14	10	12	14	12	14	11	14	13

TABLE 11-3

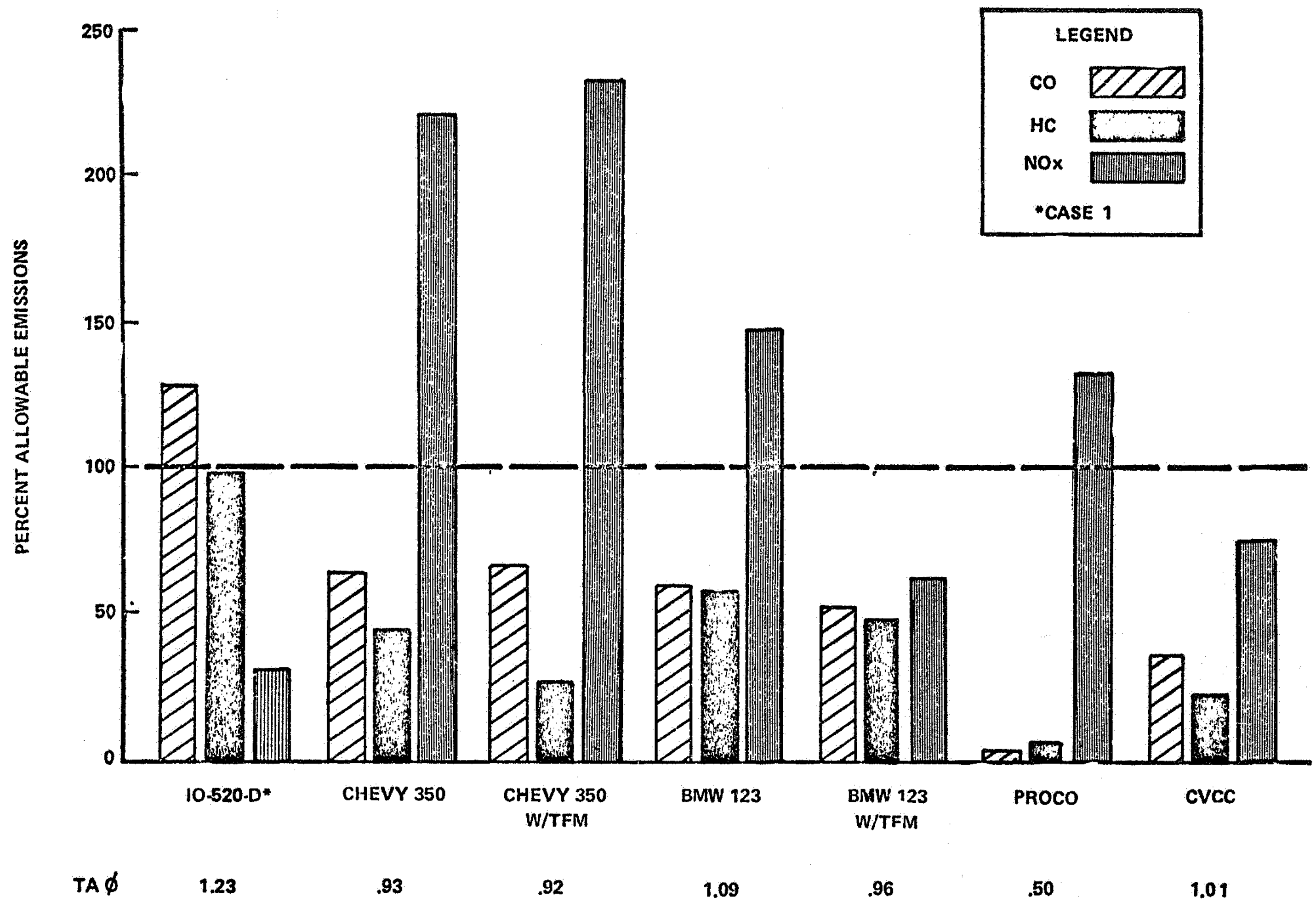
EMISSIONS RANKING BASED ON EPA STANDARDS FOR CO ONLY

CONCEPT	RANK
4-STROKE DIESEL, OPEN CHAMBER	1
FORD PROCO	2
TEXACO CCS	3
2-STROKE DIESEL, MC CULLOCH	4
HONDA CVCC	5
HYDROGEN ENRICHMENT, JPL	6
IMPROVED FUEL INJECTION SYSTEMS	7
AIR INJECTION	8
IMPROVED COOLING COMBUSTION CHAMBER	9
VARIABLE IGNITION TIMING	10
THERMAL FUEL VAPORIZATION, ETHYL	11
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	12
MULTIPLE SPARK DISCHARGE SYSTEM	13
VARIABLE CAMSHAFT TIMING	14

TABLE 11-4

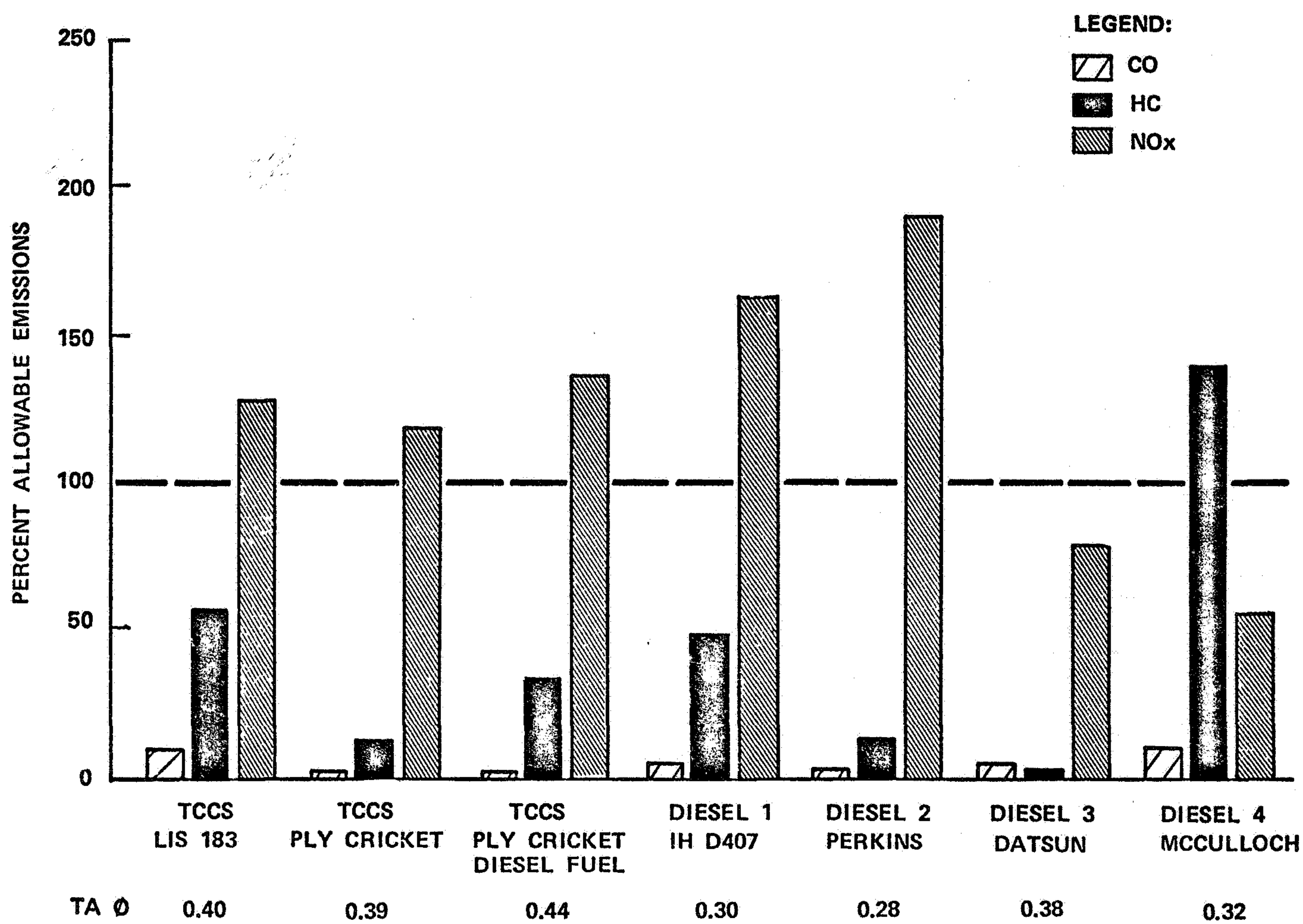
CONCEPT PREFERENCE ANALYSIS
BASED ON EPA STANDARDS FOR CO ONLY

CONCEPT	RANK
IMPROVED COOLING COMBUSTION CHAMBER	1
IMPROVED FUEL INJECTION SYSTEMS	2
MULTIPLE SPARK DISCHARGE SYSTEM	3
AIR INJECTION	4
VARIABLE IGNITION TIMING	5
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	6
THERMAL FUEL VAPORIZATION, ETHYL	7
HYDROGEN ENRICHMENT, JPL	8
2-STROKE DIESEL, MC CULLOCH	9
TEXACO CCS	10
FORD PROCO	11
HONDA CVCC	12
VARIABLE CAMSHAFT TIMING	13
4-STROKE DIESEL, OPEN CHAMBER	14



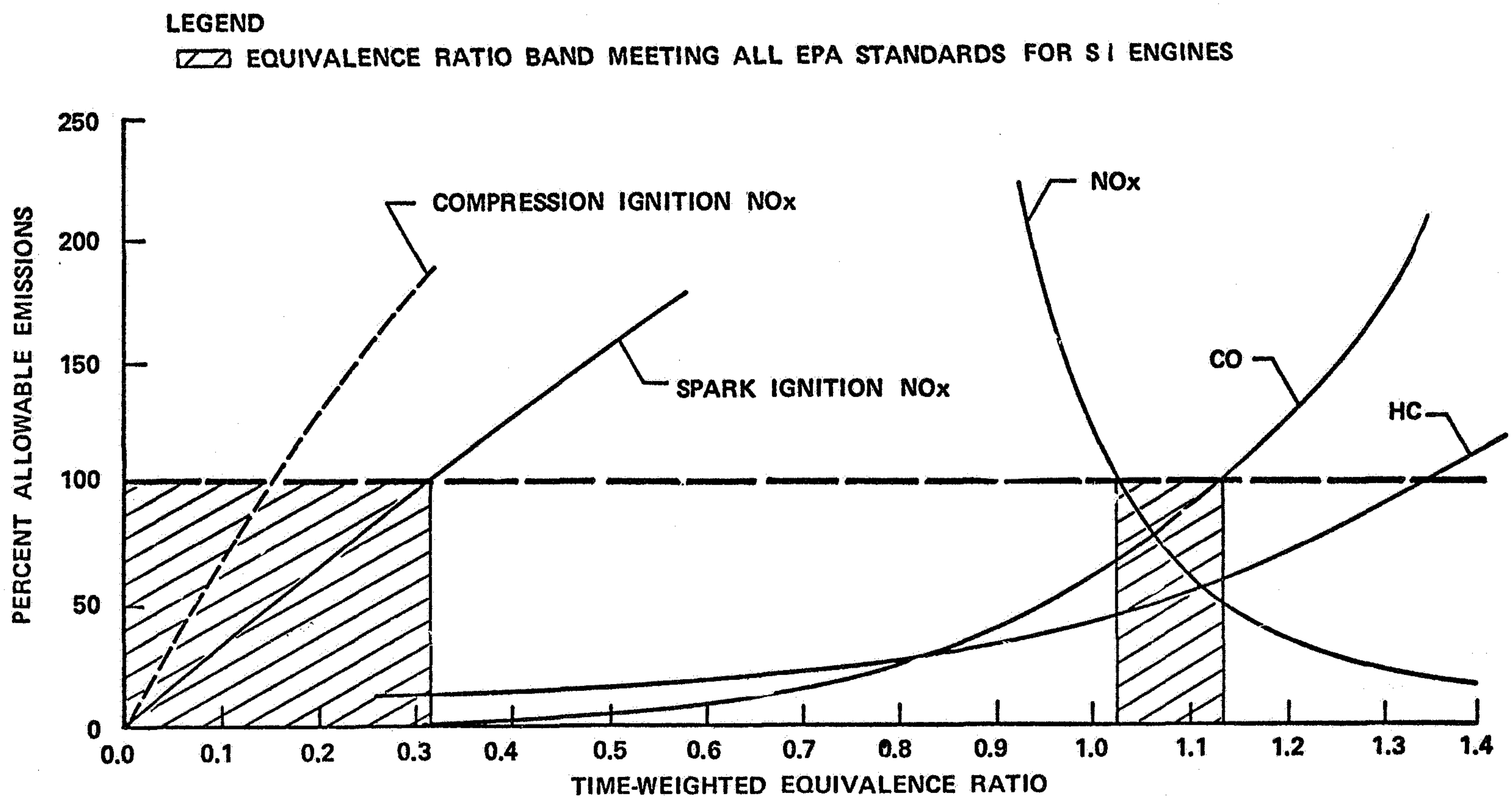
PERCENT ALLOWABLE EMISSIONS FOR CONCEPTS EVALUATED ON A 7-MODE AIRCRAFT EMISSION CYCLE

Figure 11-1



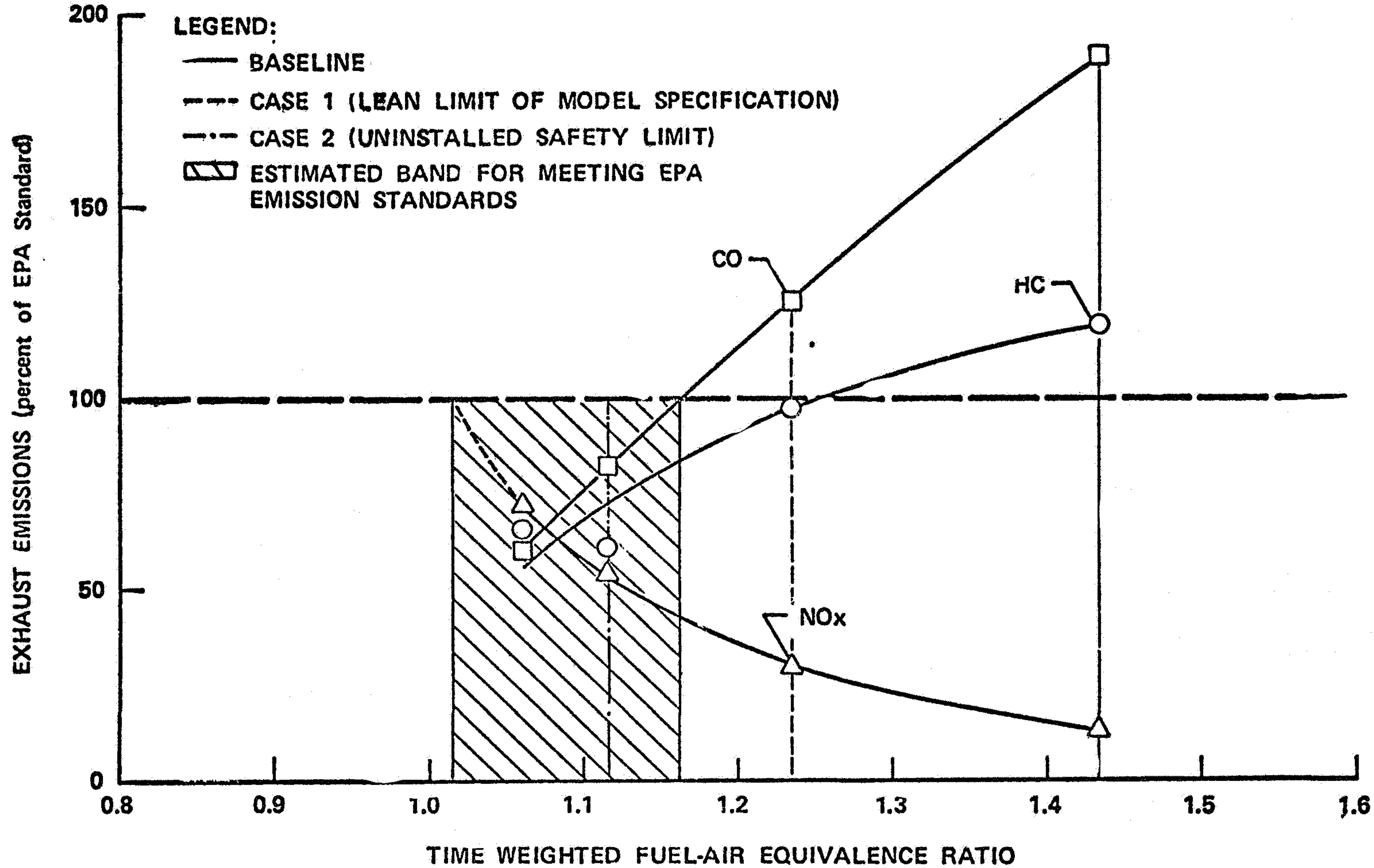
PERCENT ALLOWABLE EMISSIONS FOR CONCEPTS EVALUATED ON A 7-MODE AIRCRAFT EMISSION CYCLE

Figure 11-1. - Concluded.



PERCENT ALLOWABLE EMISSIONS VERSUS TIME-WEIGHTED EQUIVALENCE RATIO FOR ENGINES EVALUATED ON A 7-MODE AIRCRAFT EMISSION CYCLE

Figure 11-2



IO-520-D, EXHAUST EMISSION LEVELS FOR VARIOUS MIXTURE STRENGTH SCHEDULES

Figure 11-3

COST CRITERIA ELEMENT WITH A PARTIAL LISTING OF SOLUTION ATTRIBUTES

Sheet: 1 of 7

Criteria: COST

Definition:

Cost is the dollars paid by an organization for an end item or service. Cost is the expected expenditure of money for planning, engineering, manufacturing, and supportive services to realize an effective E^3R design solution approach.

Value

Attributes	Assignment
1. Will the expected cost, to produce the design approach, be high (H), moderate (M), or low (L)?	a. Give a ROM cost estimate range per concept unit: b. If ROM cost estimates cannot be made then indicate L, M, H per concept. Score (1) to the concept that has low cost indication and (0) to moderate or high.
2. Will the concept require engineering analysis and evaluation ability	

Arbitrary Cost Scale

SCALE	RANGE ($)
Low	0 to 99
Moderate	100 to 999
High	1,000 to 9,999

Figure 11-4

EFFECTIVENESS CRITERIA ELEMENT WITH A PARTIAL LISTING OF SOLUTION ATTRIBUTES

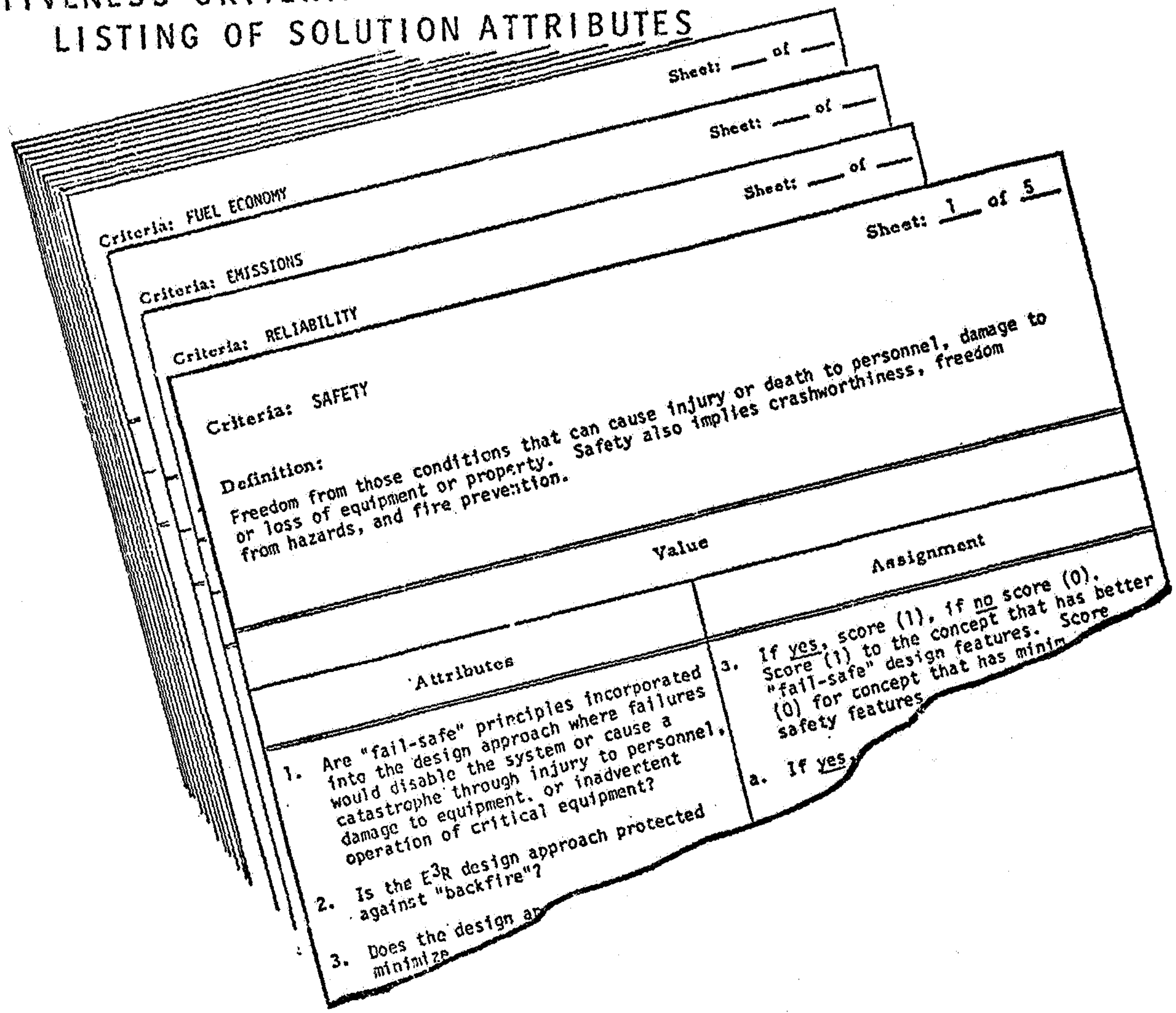
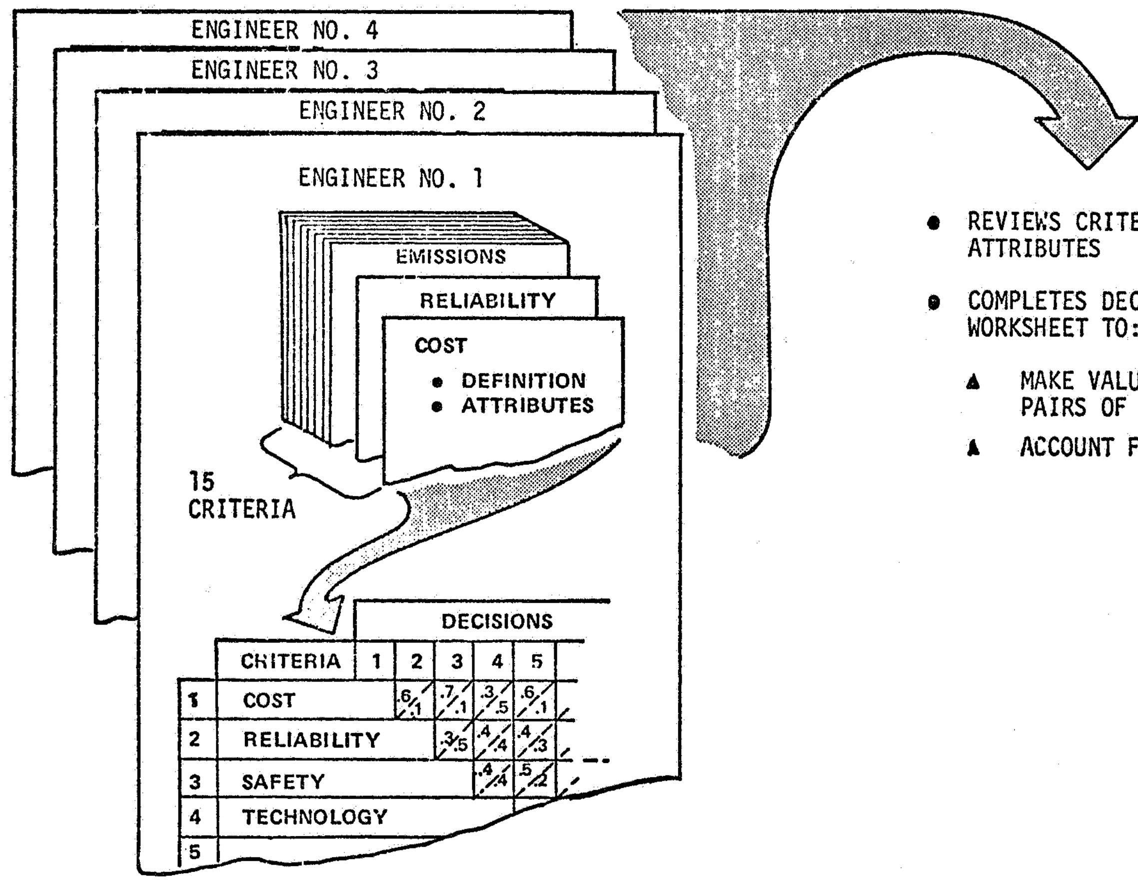


Figure 11-5

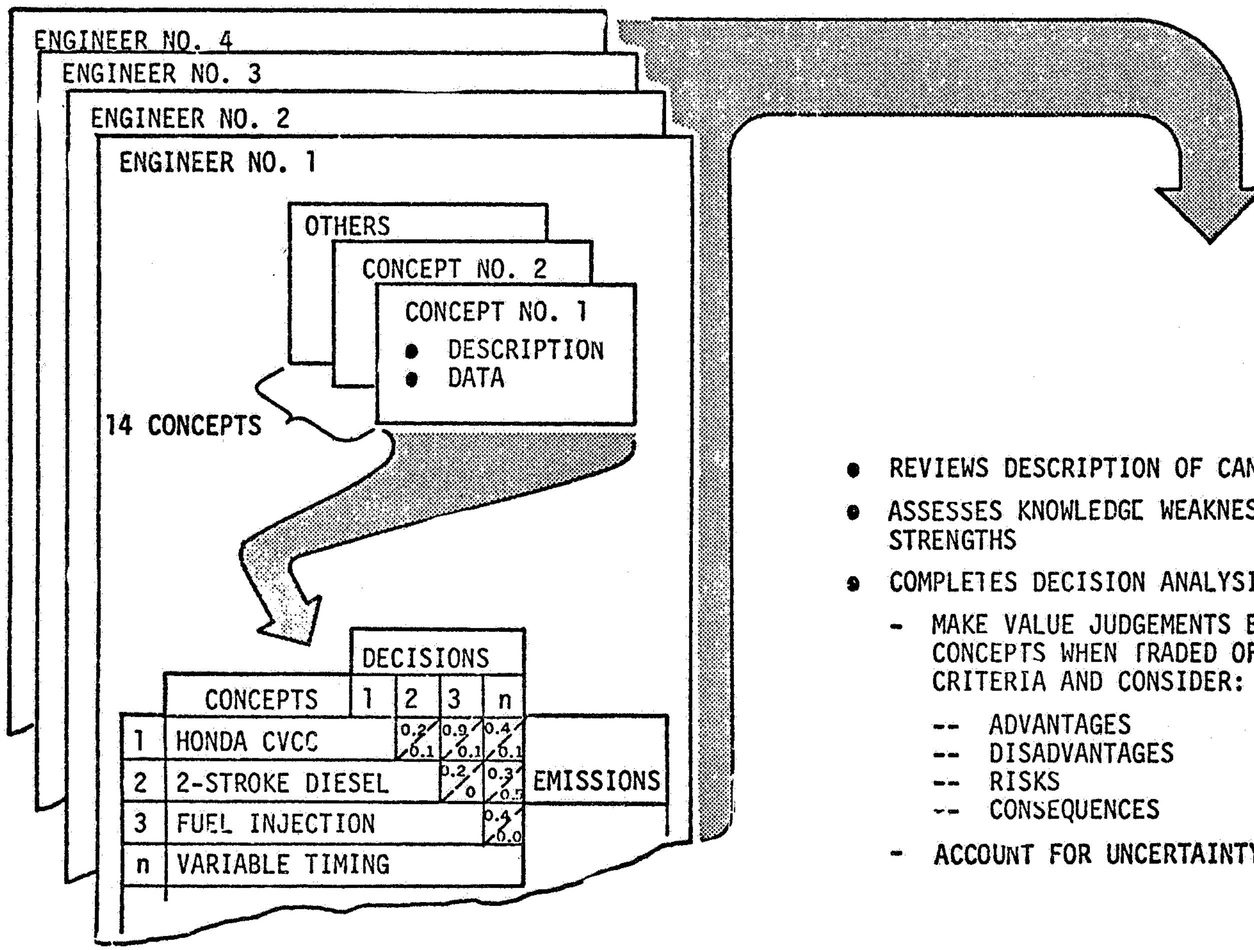
PROCEDURE FOR EVALUATING THE RELATIVE IMPORTANCE OF CRITERIA



- REVIEWS CRITERIA AND SOLUTION ATTRIBUTES
- COMPLETES DECISION ANALYSIS WORKSHEET TO:
  - ▲ MAKE VALUE JUDGMENTS BETWEEN PAIRS OF CRITERIA
  - ▲ ACCOUNT FOR UNCERTAINTY

Figure 11-6

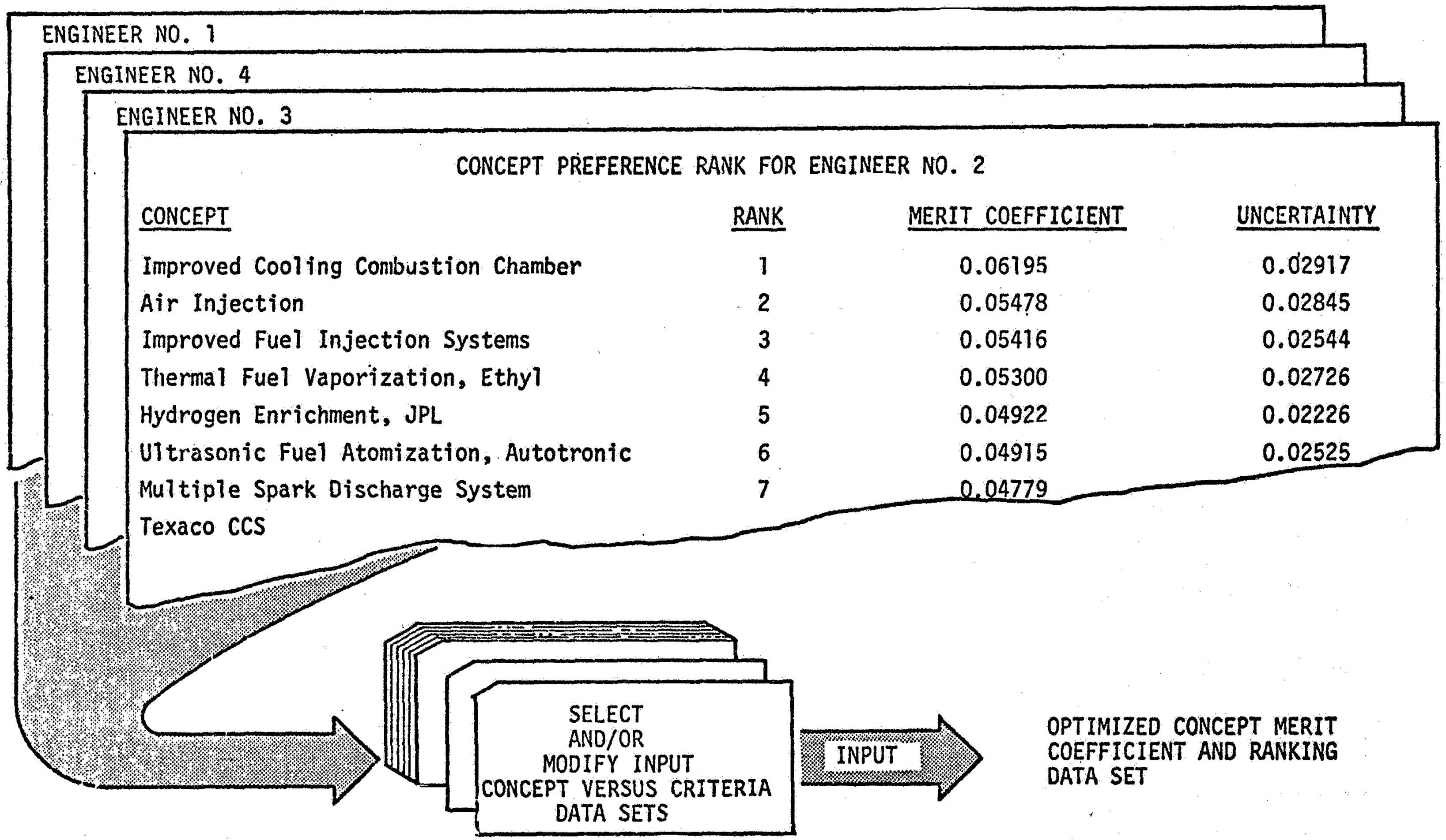
PROCEDURE FOR EVALUATING THE RELATIVE IMPORTANCE OF CONCEPTS



- REVIEWS DESCRIPTION OF CANDIDATE DESIGN CONCEPTS
- ASSESSES KNOWLEDGE WEAKNESSES AND EXPERTISE STRENGTHS
- COMPLETES DECISION ANALYSIS WORKSHEETS TO:
  - MAKE VALUE JUDGEMENTS BETWEEN PAIRS OF CONCEPTS WHEN TRADED OFF AGAINST THE CRITERIA AND CONSIDER:
    - -- ADVANTAGES
    - -- DISADVANTAGES
    - -- RISKS
    - -- CONSEQUENCES
  - ACCOUNT FOR UNCERTAINTY

Figure 11-7

EXAMPLE OF CONCEPT PREFERENCE RANKING



CONCEPT PREFERENCE RANK FOR ENGINEER NO. 2

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Cooling Combustion Chamber	1	0.06195	0.02917
Air Injection	2	0.05478	0.02845
Improved Fuel Injection Systems	3	0.05416	0.02544
Thermal Fuel Vaporization, Ethyl	4	0.05300	0.02726
Hydrogen Enrichment, JPL	5	0.04922	0.02226
Ultrasonic Fuel Atomization, Autotronic	6	0.04915	0.02525
Multiple Spark Discharge System	7	0.04779	
Texaco CCS			

Figure 11-8

DATA FLOW PROCESS TO ACQUIRE CONCEPT RANKING

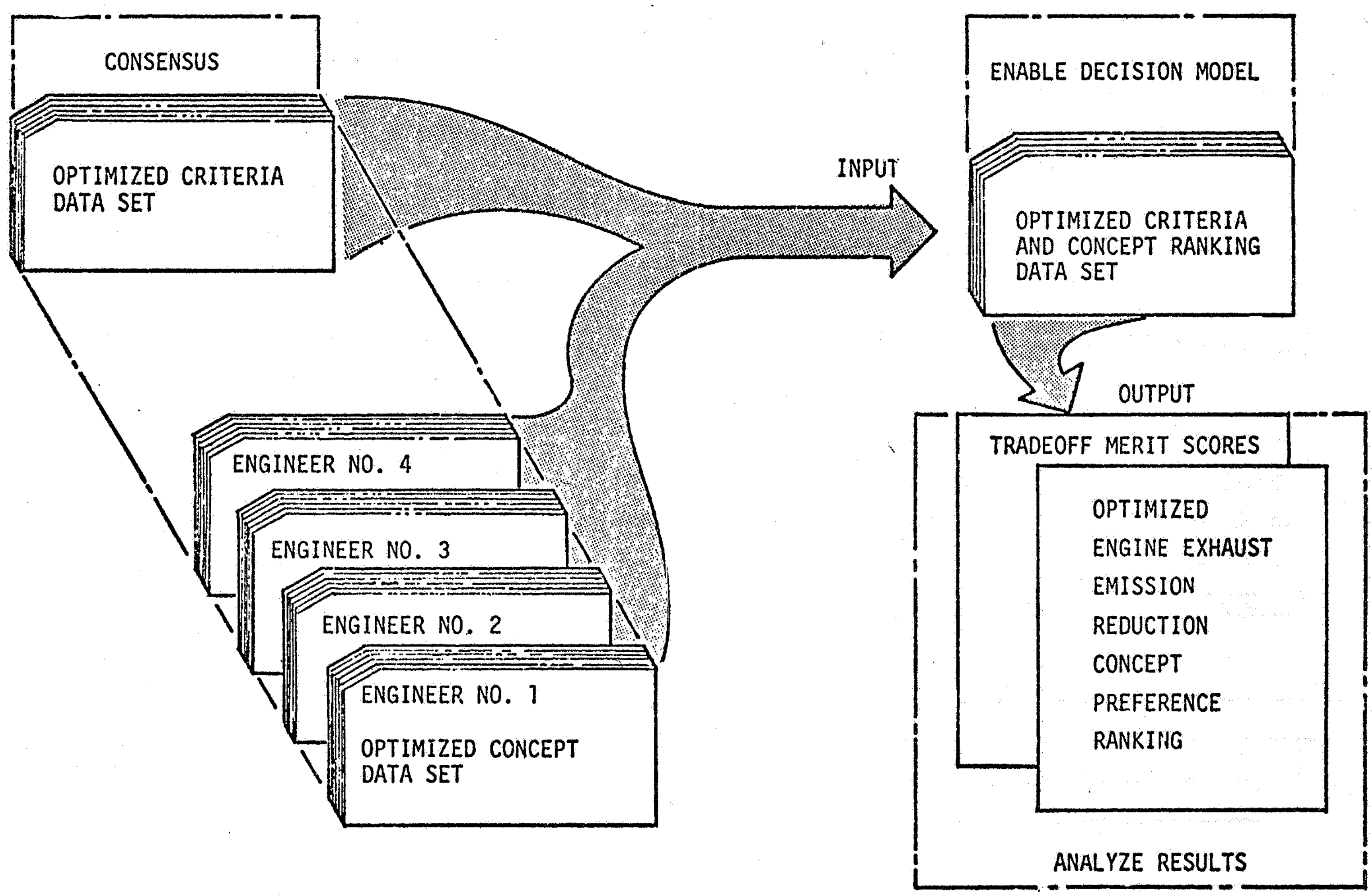


Figure 11-9

ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANKING - OPTIMIZED

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
EMISSIONS	0.10952	0.00138
SAFETY	0.09676	0.00750
PERFORMANCE	0.08714	0.00701
COOLING	0.07695	0.00707
WEIGHT AND SIZE	0.07238	0.01159
FUEL ECONOMY	0.06990	0.01020
COST	0.06771	0.01192
RELIABILITY	0.05933	0.00903
TECHNOLOGY	0.05548	0.00658
OPERATIONAL CHARACTERISTICS	0.04200	0.01059
MAINTAINABILITY AND MAINTENANCE	0.04029	0.00924
INTEGRATION	0.03324	0.00295
MATERIALS	0.03029	0.00305
PRODUCIBILITY	0.02933	0.00210
ADAPTABILITY	0.02781	0.00267

Figure 11-10