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PROPULSION WORKING GROUP REPORT

James Mavrogenis, Chairman
Hughes Aircraft Company

James Kelley, Cochairman
Jet Propulsion Laboratory

James Stone, Cochairman
NASA Lewis Research Center

POSITION STATEMENT

As high payoff propulsion technologies for application in the year 2000 and beyond were identified, it became obvious that many of them had been initially worked on in the 1960's and 1970's. In most cases their development was halted not by technological impasses but by the lack of funding, driven in part we believe, by a short term payoff mind-set within the decision-making establishments in Government. Although the high payoffs of these technologies were obvious to industry, the high development costs, the associated risks, and the absence of an immediate application precluded private development. No national policy existed or currently exists that recognizes the Government's responsibility to fund the constant and steady development of technology as a national resource. The technology being researched and developed for the SDI could be cited as an attempt to provide such as policy, but it falls far short of the mark for many reasons including being tied to a specific application.

We believe that the greatest benefit that could come from the Spacecraft 2000 initiative would be the realization at the highest levels of Government of the real losses the country has sustained in space leadership because of the short term mentality that has controlled the development of high payoff space technologies. The Spacecraft 2000 steering committee should assume a leadership role in bringing this message to the Congress. It should then assist in the definition and establishment of a long term technology development program.

POSITION STATEMENT

MANY ADVANCED PROPULSION TECHNOLOGIES HAVE BEEN DEMONSTRATED OVER THE LAST 20 YEARS. FRAGMENTED FUNDING AND A LACK OF AWARENESS OF THE HIGH PAYOFFS HAVE KEPT THE TECHNOLOGY FROM BEING DEVELOPED. DEVELOPMENT COSTS AND RISKS PRECLUDE PRIVATE FUNDING OF THESE TECHNOLOGIES.

SELECTION CRITERIA

It is obvious that not all the propulsion technologies that are identified in this briefing can or should be developed for application by the 21st century. The four selection criteria identified here have been chosen so that the technologies with the highest payoff - a term whose definition is mission dependent - can be identified for continued development. Also mission dependent is the weight that each criteria should carry in an evaluation. Weighting the criteria was beyond the scope of the working group meeting but should be addressed in a subsequent working group meeting.

This working group believes that technologies should be developed as a national resource. As such, the use of the term "mission" above implies not a specific spacecraft mission but a national space policy. By way of example, if our national goal was the manned exploration of the planets, then propulsion technologies which offered the shortest trip time should be selected. These same technologies would most likely be unsuitable if our national space goal was development of the space station's capabilities.

Technologies which reduce the dry weight of a propulsion system or which deliver a greater specific impulse (performance) from each pound of system loaded weight offer the highest payoff. Except for manned missions this criteria should carry the greatest weight in the selection evaluation. System reliability and safety enhancing technologies should carry the greatest weight for manned missions. The last two criteria, cost and risk, refer to the development of each technology. With limited resources it is imperative that the benefit promised by each technology be weighed against the cost and risk of successfully bringing forth a mature capability. We must also recognize that any such assessment is highly subjective and will sometimes result in technology development false starts and program deadends.

PROPULSION-SPECIFIC TECHNOLOGY

SELECTION CRITERIA

- o PERFORMANCE
  - HIGHER MASS FRACTION/I_{SP}
- o RELIABILITY & SAFETY
- o COST
- o RISK

EXISTING TECHNOLOGY LIMITS

This chart illustrates the payoff from a modest 20% improvement in specific impulse. Technologies exist, e.g. ion propulsion which offer a 1000% improvement in specific impulse resulting in nearly a five fold increase in payload weight delivered to geosync orbit by the shuttle if such a system was used to propel the transfer vehicle. The sad truth is that while the U.S. debates the development of giant rockets capable of boosting the enormous SDIO weights into orbit, ion propulsion systems which could eliminate the need for giant new boosters have been demonstrated in space and yet remain unapplied.

EXISTING TECHNOLOGY LIMITS & PERFORMANCE

- o 20% TYPICAL PERFORMANCE IMPROVEMENT IN SPECIFIC IMPULSE GIVES HIGH PAYOFF.

GEOSYNC EXAMPLE

- o 100% GREATER PAYLOAD CAPABILITY

	@ EXISTING I_{SP}	@ I_{SP} INCREASED
	200-300 SEC	20%
PAYLOAD MASS	500 LBS	1,000 LBS
SPACECRAFT (BUS)	1,500	1,500
DRY	2,000	2,500
7 YR GEO PROPELLANT	600	600
BEGIN GEO	2,600	3,100
APOGEE PROPELLANT	2,600	2,500
GTO	5,200	5,600
PERIGEE PROPELLANT	5,200	4,500
LEO	10,400	10,100
TOTAL PROPELLANT MASS	8,400 LBS	7,600 LBS

KEY TECHNICAL PROBLEMS IN CURRENT S/C PROPULSION

- AT LIMITS OF CURRENT PROPELLANT PERFORMANCE
- APPROACHING MATERIAL LIMITS
  - PERFORMANCE
  - LIFE
  - PROCESSES
- FEED SYSTEM DESIGN
  - HEAVY
  - PROPELLANT GAGING ACCURACY
- LACK OF STANDARDIZATION
- LACK OF SPACE SERVICEABILITY
- PLUME PROBLEMS
  - IMPINGEMENT
  - CONTAMINATION

NEAR-TERM RECOMMENDATIONS - HIGH PAYOFF TECHNOLOGIES

The high payoff technologies identified should be pursued in the near term, but funding realities make it unlikely that all could be pursued simultaneously at significant levels. Therefore, studies should be undertaken to quantify the benefits of these technologies to a wide range of missions. The results of these studies, along with a projection of the time frame when the technology is required for each major type of mission, should allow the planning of a technology development and demonstration program resulting in the greatest payoff within the resources provided.

HIGH PAYOFF TECHNOLOGIES

- ADVANCED BIPROPELLANT SYSTEMS
- ELECTRIC PROPULSION SYSTEMS
- PROPELLANT FEED SYSTEM TECHNOLOGIES
- THESE TECHNOLOGIES HAVE DEMONSTRATED FEASIBILITY. CONSTANT GOVERNMENT FUNDING IS REQUIRED TO BRING THEM TO A TECHNOLOGY READINESS STATE.
- PRIORITIZATION IS DRIVEN BY MISSION MODEL.

PROPULSION TECHNOLOGIES

A number of technologies and related issues which should be addressed were identified. Those thought to have the highest potential payoff, which will be discussed in more detail, are the following:

Advanced Bipropellant Systems
Electric Propulsion Systems

A high payoff is also expected from

Advanced Materials
Standardization
An In-Space Test Bed

In addition to these, there are several other areas which should not be neglected. Plume modeling is needed to allow prediction of the interaction of the thruster exhaust with the spacecraft, particularly for payloads where contamination is an issue. Valid data and models do not presently exist for plumes from small rockets. Verification of such models is a major justification for the In-Space Testbed. The ability of refuel and service propulsion systems is space should be considered, even though it may pay off only for a few specific cases. The development of automated, expert system design aids would be a cost saver. The manufacture of propellants in space could open new option; of particular interest is the electrolysis of water to produce H_2 and O_2. The analysis of potential payoffs for all of these technologies should be a part of the program planning process and should be updated as the program progresses.

PROPULSION TECHNOLOGIES

* ADVANCED BIPROPELLANT SYSTEMS

* ELECTRIC PROPULSION SYSTEMS

* PROPELLANT FEED SYSTEM TECHNOLOGIES

* ADVANCED MATERIALS

* STANDARDIZATION

PLUME MODELING

* IN-SPACE TEST BED

ABILITY TO SERVICE IN SPACE

AUTOMATED DESIGN

SPACE MANUFACTURING OF PROPELLANTS

ANALYSIS OF PAYOFFS FOR EACH TECHNOLOGY AS PART OF THE PROGRAM PLANNING PROCESS

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* INDICATES FURTHER DETAIL IN FOLLOWING CHARTS.

C-3

ADVANCED BIPROPELLANT SYSTEMS

Advanced bipropellant systems offer payoffs to a wide range of missions. A number of potential high-energy propellant combinations, such as N_2O_4/N_2H_4, CIF_5/N_2H_4 (or blends), and F_2/N_2H_4, should be evaluated and the most promising selected for advanced development. All of these propellant combinations have greater performance than present N_2O_4/MMH systems and all have been ground tested. In addition, in each of these cases, hydrazine is the fuel and could be used as a monopropellant for attitude control. The propellant combinations are listed in increasing order of I_{sp} and increasing order of technical difficulty. N_2O_4/N_2H_4 is state of the art but a system to use it in spacecraft has not been developed. The CIF_2 system is not cryogenic; the F_2 system is, but has the highest performance of the group.

High temperature thruster materials, including rhenium, composites and ceramics should be investigated to allow the minimization of cooling flows, thereby increasing performance, while offering very large increases in lifetime.

ADVANCED BIPROPELLANT SYSTEMS

o EVALUATE HIGH-ENERGY BIPROPELLANTS -- SELECT FOR ADVANCED DEVELOPMENT, EG:

  - N_2O_Y/N_2H_4
  - CLF_5/N_2H_4 OR HYDRAZINE BLENDS
  - F_2/N_2H_4

o EVALUATE ADVANCED ENGINES & MATERIALS; EG:

  - RHENIUM
  - COMPOSITES
  - CERAMICS

ELECTRIC PROPULSION SYSTEMS

Several electric propulsion systems offer major performance break-throughs for low thrust applications (Figs. 1,2).

Xenon Ion System:

Ion propulsion offers the highest specific impulse available by the year 2000. Ion engines have been tested successfully in space using metal vapor propellants. In order to be applicable to many missions it will be necessary to demonstrate performance in space with inert gas propellants, such as xenon.

Arcjet Systems:

Arcjet systems offer major payoffs both for station keeping (Fig 3) and orbit transfer applications.

Low-power arcjets represent the next logical step in hydrazine propulsion beyond current state-of-art resistojets. (Fig 4) Laboratory testing has established the feasibility of such a system at the appropriate thrust and power levels. Further ground testing is needed to optimize the system and to establish performance/lifetime trades. In-space testing will be required to address critical integration issues such as plume effects and EMI.

High-power arcjets using ammonia propellant and, in the future, hydrogen, are promising for orbit transfer.

Higher Thrust Pulsed Plasma Thrusters:

Pulsed plasma thrusters are used in applications where very precise impulse bits are required.

ELECTRIC PROPULSION SYSTEMS

- XENON ION SYSTEM
- ARC JET SYSTEMS
  - LOW POWER (STATION KEEPING)
  - HIGH POWER (ORBIT TRANSFER)
- HIGHER THRUST PULSED PLASMA THRUSTORS

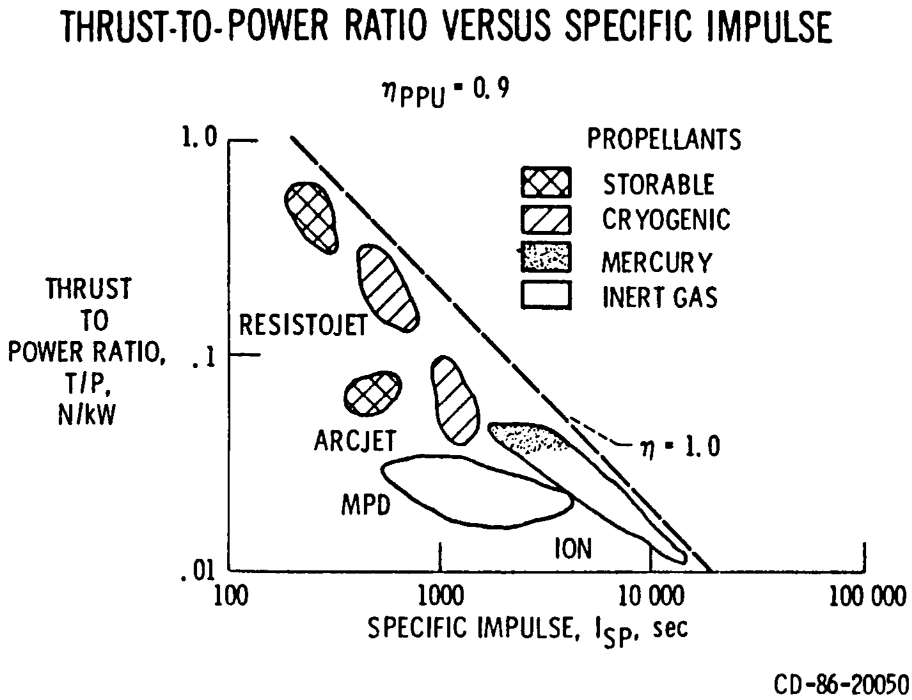

Figure 1.

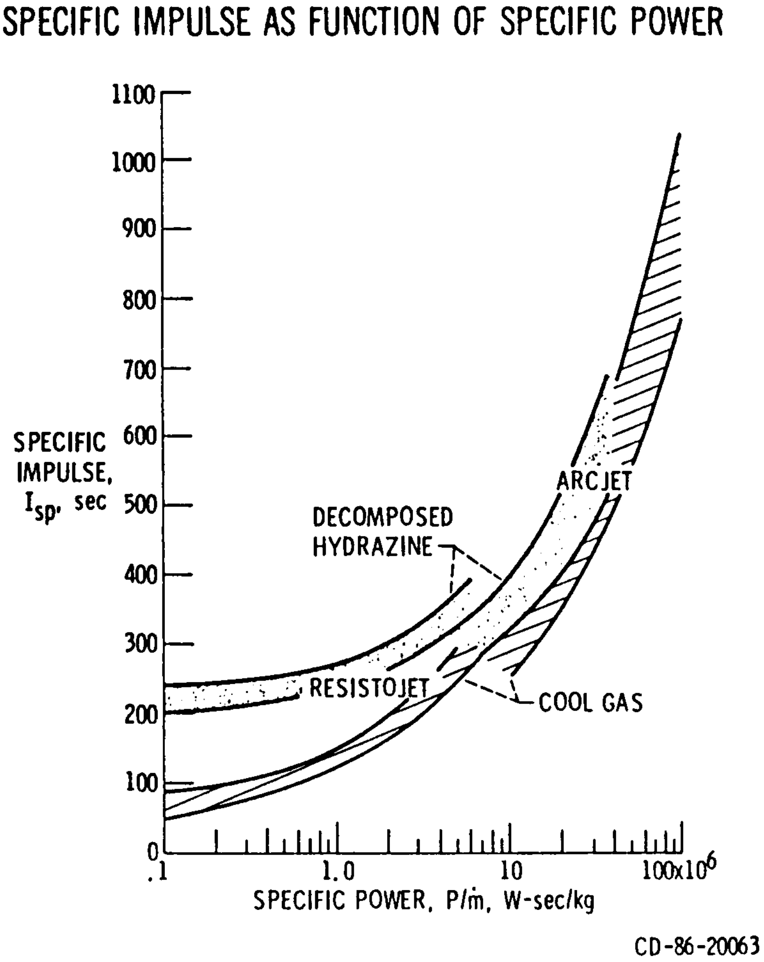

Figure 2.

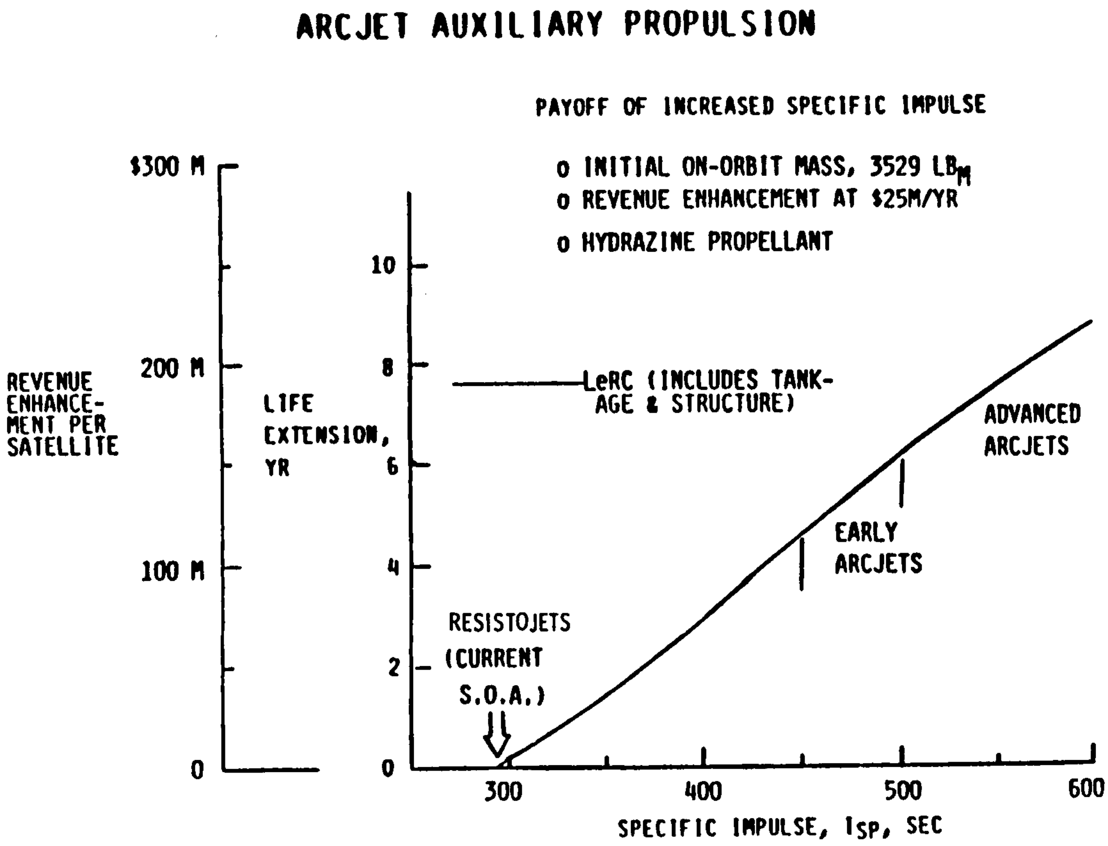

Figure 3.

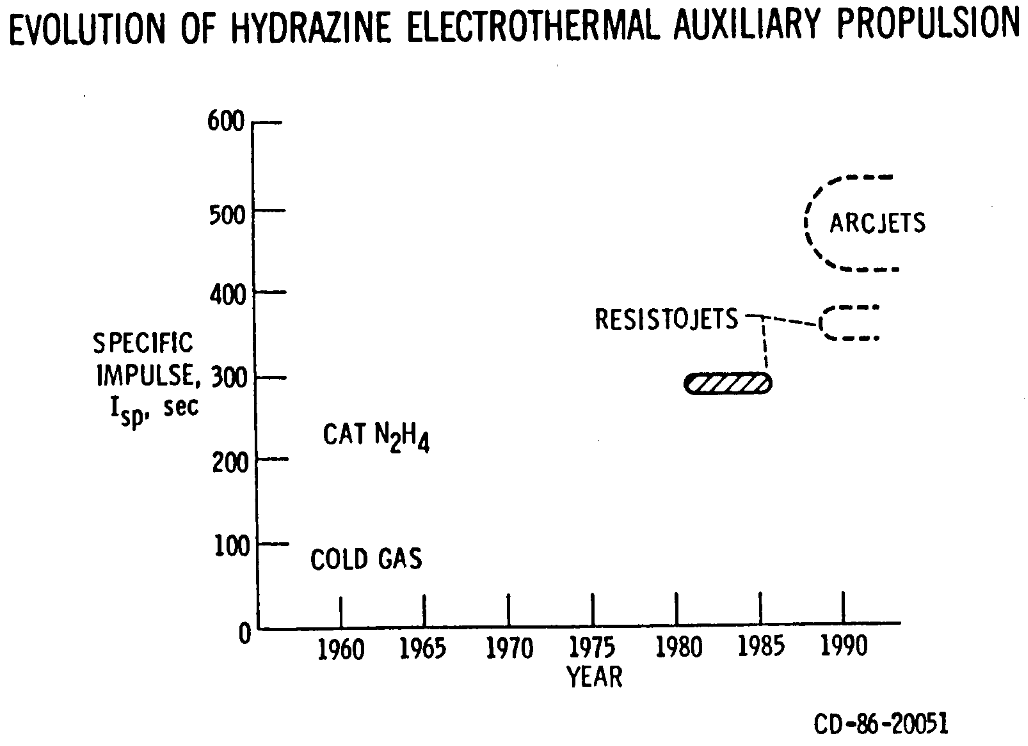

Figure 4.

MATERIALS

High-temperature, long-life chambers, seals and insulators should be developed utilizing advanced materials. This would permit longer life at current performance levels. higher performance at current lifetime, or increases in both performance and life.

A materials compatibility data base is required for both chemical and electrical propulsion systems. For example, current data in the literature is often of limited use in predicting materials compatibility since the operational environments in present or projected spacecraft are significantly different than those considered in past work designed for earlier missions. In particular, many of the spacecraft temperatures (high and low), propellant/material combinations, passivation techniques, filter/injector orifice sizes and mission durations are not covered by the existing data base. Finally, much of the existing data is difficult to interpret since only limited systematic testing has been done to date.

MATERIALS

- DEVELOP HIGH-TEMPERATURE, LONG-LIFE CHAMBERS, SEALS AND INSULATORS
  - CERAMICS
  - ELASTOMERS
  - METALLICS
- DEVELOP MATERIALS COMPATIBILITY DATA BASE
  - PROPELLANTS
  - EXHAUST PRODUCTS

PROPELLANT FEED SYSTEM TECHNOLOGY

- PUMPS
- LIGHT WEIGHT TANKS
- IMPROVED PLUMBING
  - FLEXIBLE JOINTS/LINES
  - ZERO LEAK DISCONNECTS
- IMPROVED VALVES
  - LEAKAGE, LIFE, WEIGHT
  - REMOTE CONTROL FILL VALVES
- INCREASED ACCURACY INSTRUMENTATION/ CONTROL SYSTEMS
- BETTER UNDERSTANDING OF PMDS

ROCKET EXHAUST PLUME MODELS/DATA

It is often said that experiment s are needed to validate plume/contamination analysis codes. Such validation tests generally evolve into end-to-end measurements such as deposition on a QCM. The final results are like "X mg/cm^2 of deposit was collected after N_1 firings of N_2 sec. total duration". Occasionally, the deposit will be identified as having a given rate of desorption or qualitative measurements of composition (e.g. "contained nitrates") will be given. State-of-art plume codes will not accurately predict these results and may not even be designed to do so.

The cause of any discrepancies between predictions and such end-to-end measurements cannot be determined from the measurements themselves. This is because (especially as related to contamination from biprops) the error could be in any of three areas:

1) Prediction of composition at the exit plane, where state of art codes ignore mixing rates, use empirical correlations (i.e. atomization parameters) beyond their range of validity, and require thermochemical data that has never been measured.

2) Plume transport phenomena, where (except for DSMC calculations) species separation and other rarefaction effects are ignored.

3) Capture and chemical interactions of plume species on spacecraft surfaces, which is a virtually virgin field. Modules in CONTAM which purport to deal with this talk of equilibrium reactions and other assumptions that cannot be justified by existing observations: (in equilibrium diamonds turn to graphite and no containment would persist forever in a vacuum).

The motivation for space-based experiments is that the plume transport cannot be accurately modeled in ground-based vacuum chambers. Paradoxically, this is the best understood area of the three. Work that is more valuable would determine what assumptions are valid for, and thermophysical properties that are needed to analyze, the first and third areas. These could take the form of:

1) Tomographic transmission spectroscopy or other techniques to find exit plane composition.

2) High time-resolution measurements of exit plane properties and intermittancy to study mixing effects.

3) Molecular beam studies of molecular sticking and chemical reactions as a function of:

   a) impingement velocity (1 --> 5 km/s)
   b) substrate (crystal planes --> thermal control point)
   c) incidence angle
   d) beam intensity
   e) substrate temperature
   f) etc.

4) Determination of impacts of low (non-zero) cont. levels on instruments.

With this sort of program, NASA, DoD and industry could start to define requirements and input data for codes that could be expected to pass validation (i.e. end-to-end) tests.

STANDARDIZATION

Standardization of documentation, although not a technology, when correctly applied can save funds that could be better spent in technology development. With respect to hardware, the intent is to standardize on the size of items such as valves, regulators, and possibly thrust levels for small control engines. There is no intent to suggest that components be built for stock since this would be very costly and discourage progress in propulsion technology.

STANDARDIZATION

- * o SAFETY FACTORS
- * o TEST REQUIREMENTS
- o FRACTURE MECHANICS
- o CONTAMINATION MODELS
- * o TEST PROCEDURES
- o PROPULSION COMPONENTS
  IE REGULATORS, VALVES, THRUSTER SIZE
- * o DOCUMENTATION
  EMPHASIZE REDUCTION

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* GOVERNMENT/INDUSTRY WORKING GROUP - COST SAVINGS

IN-SPACE TEST BED

Some of the new technology cannot be validated in ground test but instead requires space-based testing. Technologies such as plume/contamination model validation, analyses of ion and arcjet propulsion interaction with the spacecraft and propellant gaging concepts tested in a zero-gravity environment all require a space-based platform. What is envisioned is a simple spacecraft deployed from the shuttle and retrieved on a subsequent flight. The important characteristics for such a vehicle are identified in the chart. The most important of these is early availability. For technologies to be available by the year 2000, testing needs to be accomplished before 1995 to allow time for development, retest and qualification.

IN-SPACE TESTBED

- o DESIRED CHARACTERISTICS
  - EARLY 1990's AVAILABILITY
  - MODULAR POWER (MULTI-KW)
  - REUSABLE OR RETURNABLE
  - DURATION OF A FEW MONTHS
  - EMI MEASUREMENTS
  - ZERO SELF-CONTAMINATION
  - ACCURATE MEASURE OF IMPULSE

POST-2000 TECHNOLOGIES

The technologies discussed so far are all evolutionary in nature. While they will in many cases, e.g. ion propulsion, provide substantial improvements over current designs the truly dramatic improvements will come from the technologies listed in the chard. These technologies should be evaluated against a background of current knowledge to determine which ones warrant a low level of development effort now and which of these, lacking the necessary supporting technologies can be set aside for review in 5 years. Of those listed, a magneto plasma dynamic thruster appears to have the lead in earliest development.

POST-2000 PROPULSION TECHNOLOGIES

(REVOLUTIONARY CONCEPTS)

THERE ARE A NUMBER OF REVOLUTIONARY (AS OPPOSED TO EVOLUTIONARY) TECHNOLOGIES THAT SHOULD BE PURSUED IN THE 1986-2000 TIME FRAME. THESE TECHNOLOGIES WILL PROBABLY NOT BE READY IN 2000, BUT WORK NEEDS TO BE INITIATED NOW SO THE TECHNOLOGY WILL BE READY WHEN ITS NEEDED.

- MAGNETO-PLASMA DYNAMIC THRUSTERS
- MICROWAVE PROPULSION
- SOLAR SAILS
- SOLAR-THERMAL THRUSTERS
- LASER PROPULSION
- NUCLEAR FUSSION PROPULSION
- HIGH ENERGY METASTABLE PROPELLANTS (H_4, ETC)
- ANTI-MATTER PROPULSION

RECOMMENDATIONS FOR THE GOVERNMENT/INDUSTRY RELATIONS GROUP

- o TO BE USED NEW TECHNOLOGIES NEED TO BE BROUGHT THROUGH FULL SCALE DEVELOPMENT BY THE GOVERNMENT
- o STANDARDIZATION
  - SAFETY FACTOR
  - TEST REQUIREMENTS/PROCEDURES
  - SPECIFICATIONS
- o DOCUMENTATION REDUCTION