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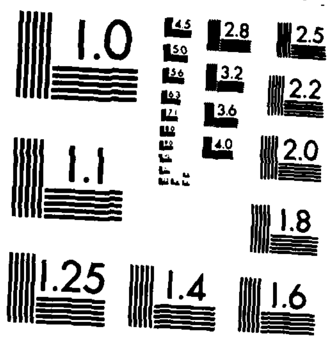

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FUTURE COMBAT ENVIRONMENTS:
IMPLICATIONS FOR THE ENGINE DEVELOPMENT PROCESS

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July 1984

P-7006

The Rand Paper Series

The Rand Corporation, 1700 Main Street, P.O. Box 2138, Santa Monica, CA 90406-2138

FUTURE COMBAT ENVIRONMENTS: IMPLICATIONS FOR THE ENGINE DEVELOPMENT PROCESS*

BACKGROUND

The distribution, quality, and size of the threat are increasingly making the environment within which U.S. forces must operate more stringent and less predictable with respect to the time available to respond to enemy action, the location of potential conflicts, the size and composition of adversary forces, the availability and extent of support facilities, and the exposure of those facilities to enemy action. The Tactical Air Forces must be prepared to deploy quickly over long distances with minimal support resources, to operate in locations lacking well-provisioned facilities, and to sustain those operations while facing adverse force ratios, and possibly airbase attacks. Since current systems were not designed to operate in such environments, it is not surprising that they are not ideally suited to accomplish these tasks.

To operate in the more stringent combat environments of the future, future propulsion systems will have to be more reliable, durable, and maintainable. The development community has already responded with many initiatives to address the reliability and durability problems that became apparent during the 1970s. Consequently, the first half of this paper will discuss instead design features that may enhance maintainability and assess the extent to which they have been incorporated in existing engines. The second half of the paper assesses how demands for more supportable engines are influencing the amount of testing and the calendar time required to develop new engines for use in fighter and attack aircraft.

*This paper was prepared for the AIAA/SAE/ASME 20th Joint Propulsion Conference, held in Cincinnati, Ohio, on June 11-13 1984.

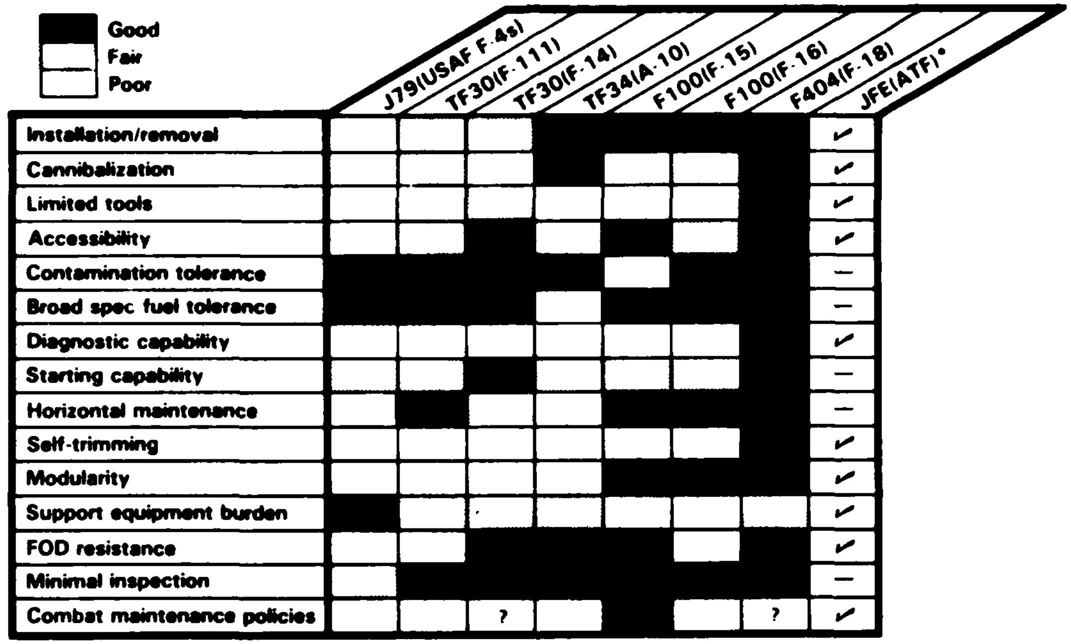
ENHANCING MAINTAINABILITY

Desirable Features

Reliability and durability aspects of engine design have received increasing emphasis in the engine development cycle during the past decade. Maintainability must receive comparable emphasis if U.S. Tactical Air Forces are to operate successfully in environments with limited or degraded support infrastructures, such as might characterize a damaged main operating base, a dispersed location in NATO or elsewhere, or an austere base in a Third Area. Sortie generation in these locations must be achievable with a minimum of deployed equipment and personnel.

Experienced Air Force and Navy engine maintenance personnel helped us identify features that could potentially ease the engine maintenance burden in such environments. None of the features noted in the first column of Fig. 1 are new ideas, but their collective embodiment in an Air Force fighter engine has not yet occurred. The list was developed with austere environment operations in mind, but each feature could potentially enhance maintainability at a main operating base as well.

Some of the rationale for assembling this list of features follows. Ease of engine installation and removal enables quick aircraft turn around which increases aircraft availability and the number of sorties that can be flown. Most maintenance people felt that an engine change should take about three men no more than a few hours to complete. Although carrying a negative connotation, the ability to rapidly cannibalize engine parts and accessories may prove essential if future forces have to operate limited numbers of aircraft from remote locations, or indeed, even from main operating bases with damaged spares inventories and infrequent resupply. In that event cannibalization may be the only way to continue to generate sorties. Minimizing the number of tools and support equipment can enhance the ability of units to deploy or redeploy. Better engine diagnostic and monitoring capabilities can reduce turnaround time spent troubleshooting and fault isolating and can enhance confidence in selecting healthy aircraft for deployment or dispersal options. Self-trimming engines can enhance mobility and reduce vulnerability to attack through reductions in the



*Draft Joint Fighter Engine Project RFP, 23 December 1982

✓ : Mentioned for consideration

— : Not mentioned

Fig. 1 — Rating maintainability features of existing engines

support equipment burden and can enhance sortie generation capability through faster maintenance turnaround.

Each feature noted in Fig. 1 has the potential for enhancing the supportability of an engine, although the inclusion of each depends on the insistence of the ultimate user of the engine and a willingness on the part of the development community to consider the features as part of the design process.

Maintainability Features in Current Engines

We asked Air Force and Navy personnel to make comparative judgments about the extent to which current engine airframe combinations possess the features noted in Fig. 1. Those judgments are shown in Fig. 1, arranged roughly in chronological order of introduction of the engine/airframe combinations.

An element colored black in the matrix means that particular system received a high or "good" grade from the maintenance personnel. The elements colored gray imply a "fair" grade, i.e., significant room for improvement exists, and a blank matrix element indicates a "poor" grade, i.e., that particular characteristic is either lacking or the task consumes an inordinate amount of clock time or manhours or both. For example, in the Air Force F-4 application, the J79 engine installation/removal receives a low mark. That engine requires about 5 clock hours and 5 people to remove, and then, on a one-shift per day basis, almost a week to refurbish the engine bay and reinstall the engine. In contrast, F100 engine removal or installation, which requires 3 men about an hour and a half, receives good marks.

The matrix shows a spotty, but improving trend prior to the F404/F-18. The F404 scores consistently high for all maintenance attributes except two--support equipment burden and combat maintenance policies. After engine removal, maintenance crews must use an additional piece of support equipment--a hoist--to move the F404 from a trailer used during engine removal to a second transportation trailer. When we spoke to Navy personnel, combat environment maintenance policies had not been issued for Navy F-18s. (For the Navy's F-18s, such policies may be unnecessary since operations from an austere, land-based site are unlikely, although the Marines may very well operate from such locations.) The marked improvement in F404 maintainability is encouraging since it is the most recently developed engine and one that was developed during a time period when operational suitability characteristics were stressed.

While most rows have at least one U.S. Air Force system that earns a "good" grade, four do not--Limited Tools, Diagnostic Capability, Starting Capability, and Self-Trimming. Engine maintenance personnel complained that the special tools required seemed excessive and often needed frequent calibration. They expressed a need for better engine diagnostics as well. In twin engine aircraft, for example, maintenance crews reported that pilots at times cannot identify which engine malfunctioned. In such cases, they must troubleshoot both engines. Criticisms about starting capability arose because when a primary starting system fails, backup systems, if they exist, prove difficult to use.

Overall, the ratings suggest an improving trend--newer engines possess more positive features than do their predecessors, although in the case of the F100 engine technology base, there exists considerable margin for improvement. Ratings by Navy personnel reflect their view that the most recent engine, the F404, is more maintainable than other Navy engines. These ratings also reflect in part the fact that engine maintainability is often installation dependent--in some respects, the F100 has proven more difficult to maintain in the F-16 than in the F-15 because of installation differences. Achieving good characteristics in each area may present difficulties because of conflicting requirements; for example the A-10's high engine location provides good protection against damage from ingestion of objects on the ground, but makes accessibility more difficult.

The F404 experience, coupled with discussions with engine contractors, suggests that no significant technological impediments prevent achieving the kinds of maintenance capabilities noted, but users must indicate their interest early in the design process if they are to be incorporated in a cost efficient manner.

TEST HOURS AND TIME TO DEVELOP ENGINES

Historically, jet engine development has emphasized increased performance at reduced engine weight. The strategy of operating at the margins of performance has usually resulted in initially low levels of reliability and durability with consequent losses of capability and increases in support cost. Cost and capability problems became particularly acute during the 1970s, increasing emphasis on enhancing engine reliability and durability. The section that follows examines how that changing emphasis has influenced the test hours and calendar time required to field new engines.

Trends In Development Test Hours

Aircraft turbine engine development has been, is, and always will be an iterative process that requires designing, building, testing, failing, fixing, and redesigning an engine until an acceptable product emerges. Development tests furnish the hard data needed to demonstrate the feasibility of the technical approach, to reduce technical uncertainty and to provide insights into engine durability at important program milestones. To determine how increasing test requirements have influenced the amount of testing accomplished during development, we reviewed select engine test experience from the late 1940s to the late 1970s using official program records supplemented by contractor data.

Demonstration and Validation Phase. Since the early 1960s the engine development community has been more clearly defining the Demonstration and Validation phase. Figure 2 shows that the most recent engine development, the F404, which best reflects increasing test requirements, accumulated three to twelve times the test hours of previous programs during the D&V phase. This increase reflects an effort to lessen risk through a program that demonstrates performance, and some key aspects of structural integrity and that produces a prototype engine of approximately the size, cycle and configuration that transitions to full-scale development.

Full-Scale Development Phase. Full-scale development test hours accumulated through the traditional Model Qualification Test (MQT) milestone have increased by about 160 percent from pre-1960 to post-

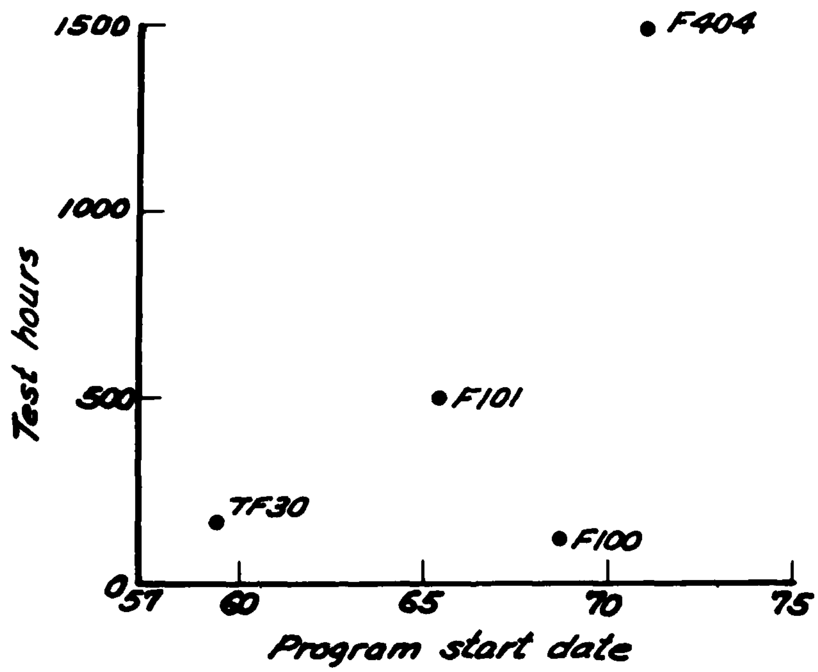


Fig. 2 — Test hours achieved during the Demonstration and Validation phase

1970 developments (see Figure 3). Test hours accumulated through the Preliminary Flight Rating Test (PFRT) milestone increased by an even greater percentage--an average of about 250 percent (see Table 1). These increases reflect growing technical difficulty, expanding requirements and increasing emphasis on more comprehensive and operationally oriented testing.

Table 1--Test Hours At Select Program Milestones
(Mean Values)

Milestones	Pre-1960s Engines	Post-1970s Engines	% Growth
PFRT	1,700	4,200	250
MQT	7,600	11,900	160

We can conclude from this review of test hours accumulations that there has been an increase in the number of test hours during the D&V phase and a step-increase in the number of FSD test hours between pre-1960s and post-1970s developments. Both reflect the increasing emphasis on improving durability and, in turn, the growth in engine qualification test requirements.

Trends in Engine Development Time

We examined engine development times to determine whether increasing testing is lengthening the time required to field new engines and complicating the phasing of their development with airframes.

Is it Taking Longer to Develop Engines? Evidence from Past Programs. We examined the acquisition time required to accomplish Demonstration and Validation phase and Full-Scale Development activities. Engine manufacturers helped us to identify program start dates, defined as the time when the government made known to the engine manufacturers its desire to have developed an engine possessing a certain set of performance characteristics. Other dates were more easily identified for the following FSD milestones:

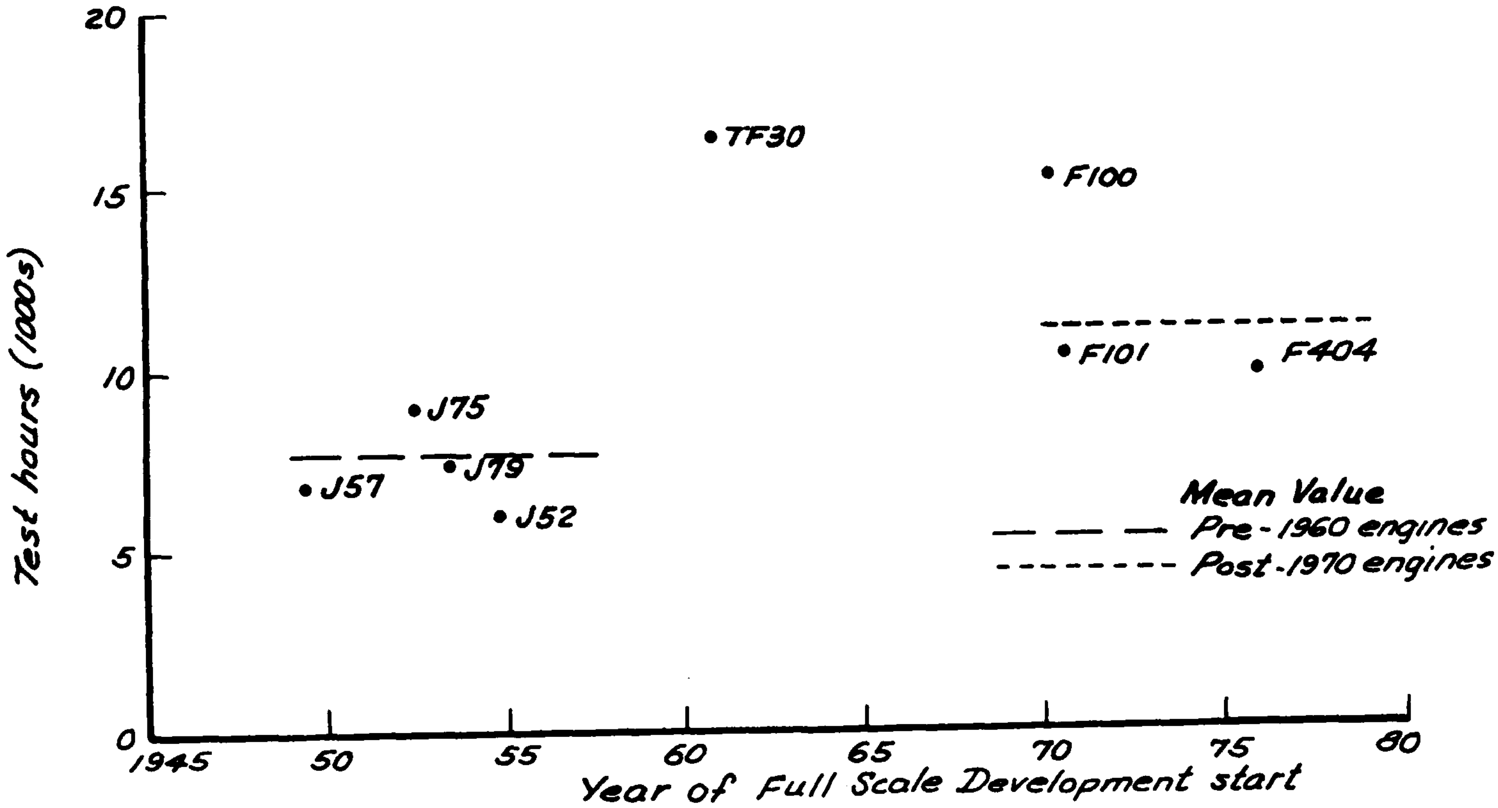


Fig. 3 — Full-scale development test hours through Model Qualification Test (MQT)

- Preliminary Flight Rating Test (PFRT)
- Model Qualification Test (MQT)
- High Production Release (HPR)

The eight engines in our data base represent the first engine in a type/model/series to pass MQT. These engines and their derivatives have powered most U.S. military fighter and attack aircraft designed and produced in the last 30 years.

No clear trend exists in the length of the Demonstration and Validation Phase. Six of the eight engines had an identifiable D&V phase. Four had a D&V phase that lasted 25 months or less, although two of the three most recent engines took about twice as long (see Figure 4). We would expect that future D&V programs will more closely resemble the longer recent programs. No trend is evident in FSD time. Figure 5 shows that the calendar time required to accomplish full scale development measured from FSD start to the traditional MQT milestone has varied within a constant range over the past 30 years.

The two most recent engines show increases in the total time to complete the development process (see Figure 6) but no conclusive trend is apparent. As emphasis on the D&V phase grows, we expect that the development time needed to qualify an engine will certainly not grow shorter.

Airframe/Engine Development Phasing. Engine development programs conducted in the past two decades have been carried out under milestone pressures arising from schedule incompatibilities of concurrent engine and airframe development. The problems resulting from a compressed development period become compounded since production lead times for engines range from 12 to 24 months and, historically, delivery of the first production engine follows shortly after MQT. Thus if FSD takes four to five years, long lead production begins while approximately one-third to one-quarter of the FSD effort remains. Concurrent engine and airframe development causes further compression of the engine development program vis-a-vis the airframe development program because the airframe manufacturer needs engines delivered three to six months prior to the aircraft delivery date.

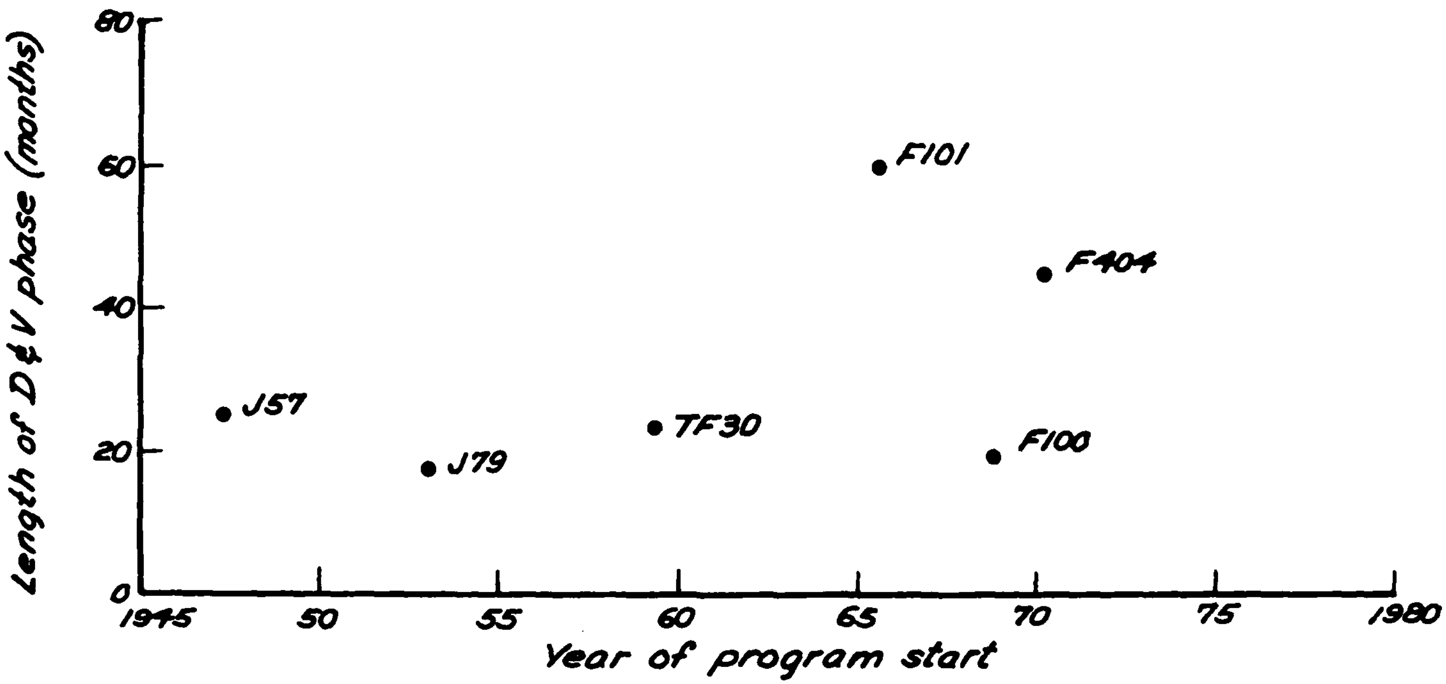


Fig. 4 — Demonstration and Validation phase duration

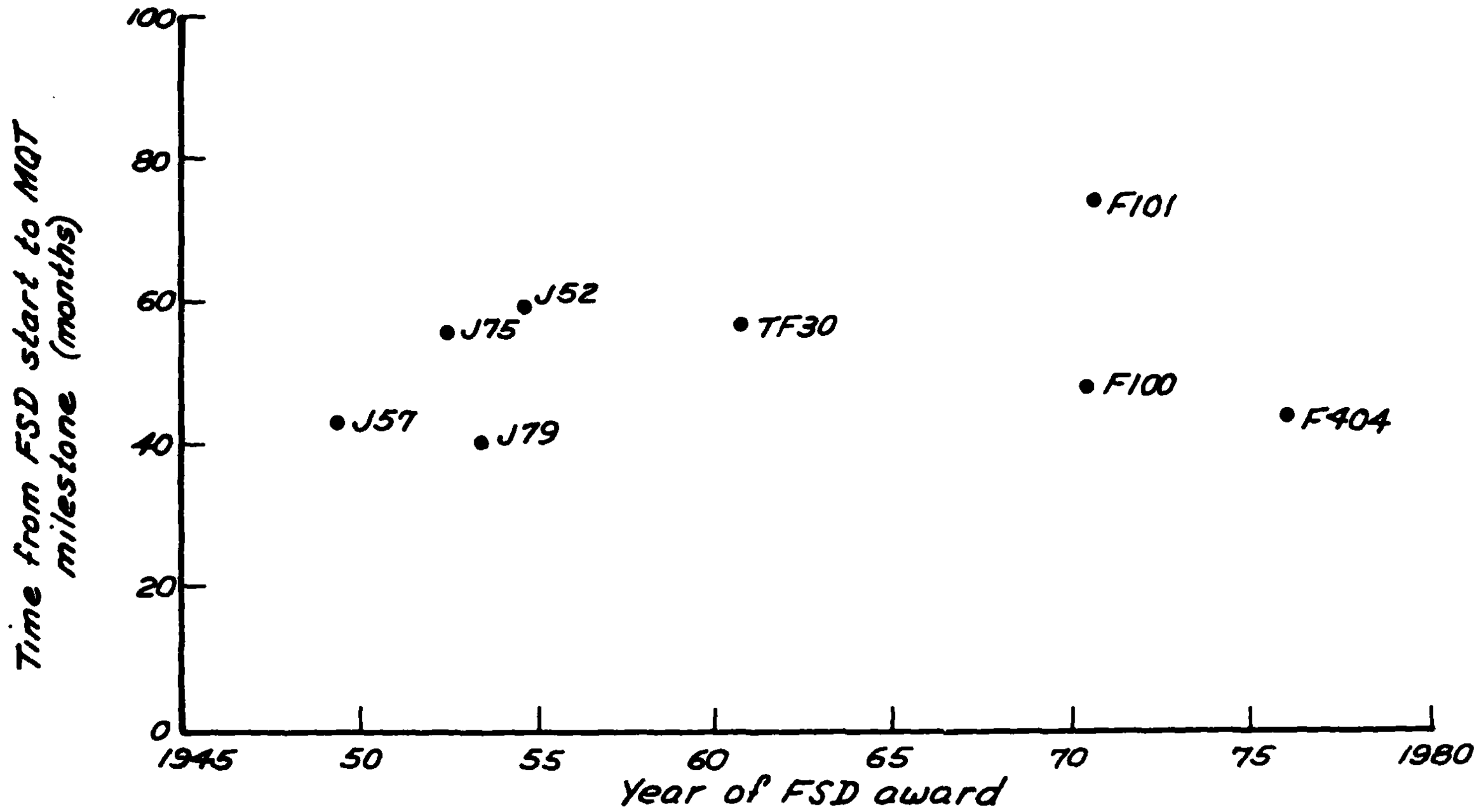


Fig. 5 – Time from Full Scale Development (FSD) award to Model Qualification Test (MQT)

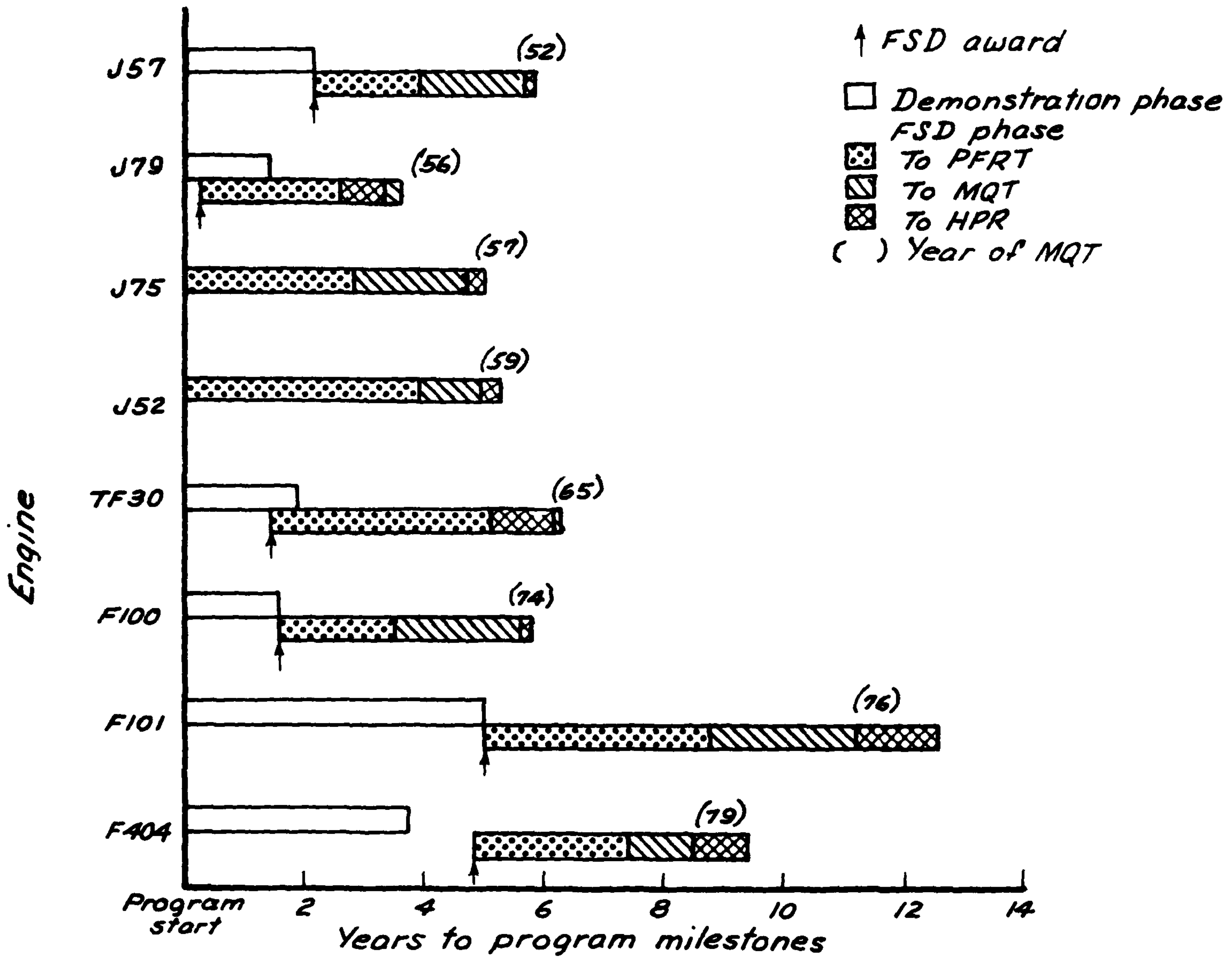


Fig. 6 — Time to accomplish program milestones

To overcome those difficulties a new engine development program needs to start almost a decade before the first aircraft delivery is scheduled. In addition, the prototype engine which emerges from the D&V phase should be the precursor of the FSD engine. That is, unlike most previous prototypes, this engine will be the approximate size, cycle and configuration of the FSD engine. This puts more pressure on the user and the acquisition community to define the operational job the engine has to do much earlier in the acquisition cycle than in the past.

SUMMARY

Propulsion subsystems will have to exhibit better reliability, durability, and maintainability to successfully operate in future environments that will be more demanding and less predictable than those which shaped the development of systems currently in the inventory. Reacting to problems experienced with 1960s and 1970s developments, the propulsion development community has undertaken a variety of initiatives to improve the reliability and durability characteristics of new engines. Some have already been put into practice by the Air Force and the Navy, while others will be tried for the first time in future programs.

To further enhance engine operational suitability we believe that:

Maintainability must receive development emphasis comparable to that being given reliability and durability if the next generation engine is to operate successfully in more stringent combat environments. Design features that can enhance engine maintainability are well known and have been demonstrated to be technically feasible in such developments as the F404. If the need for improved maintenance characteristics is stressed throughout the development cycle, impressive maintainability gains can be realized relative to current engines, enhancing operational flexibility in austere environments as well as at main operating bases. Balanced development emphasis among reliability, durability and maintainability characteristics can result in the development of engines that are responsive to the need for more operationally suitable systems.

Increasing emphasis on reliability and durability is changing the nature of the engine development process. D&V has become a more distinct, identifiable acquisition phase that is growing in calendar time and in amount of testing. Emphasis is moving away from demonstrating performance at just the design point, and instead D&V now has the objective of delivering a more mature, stable engine configuration of the approximate size, cycle, and configuration of the full-scale development engine to enable reliability and durability testing to begin earlier during full-scale development. Full-scale development test hours are not expected to increase appreciably over 1970s developments. While no conclusive trends exist, we expect that the operational suitability attributes required by future combat environments will slightly increase, compared to 1970s experience, both the time and test hours required to develop future engines.

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