Aero Engine in the New Century
— Challenge in Technology and Business —

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1. Introduction

Toasting the 100 year anniversary of controlled, powered flight, the propulsion system used on today's aircraft represents the evolution of jet propulsion based on the gas turbine, first conceived by Whittle and Von Ohain about 70 years ago. In that period, propulsion system concepts have evolved through turbo-props, turbo-jets, low by-pass ratio(BPR) turbofans to today's high BPR 2-shaft and 3-shaft turbofans. Also, this period has seen remarkable progress in the performance, reliability and environmental compatibility of these propulsion systems.

Aircraft are now three times more fuel-efficient than the early turbo-jet powered aircraft (see Fig.1), and roughly two-thirds of this improvement is due to the reduction in engine fuel consumption. There has been a significant improvement in reliability, which was especially driven by the emergence of long-range twin-engine civil transport in 1980's. Over the last 25 years, engine reliability as measured by in-flight shut-down rate has improved by more than a factor of ten (see Fig.2). Another key engine design criterion has been noise, driven by the rapid expansion of airport usage and its impact on the adjacent community. Here again, the latest engine designs are providing 25dB reduction in noise relative to the early turbo-jet powered aircraft (see Fig.3).

With these remarkable improvements behind, the growth of civil aviation has been one of the success stories of the 20th century. Over the last 40 years, annual growth in traffic (revenue passenger kilometers) has been between 5 and 6%, with only a few times of reduced traffic. Projections of future traffic by industry leaders are generally consistent

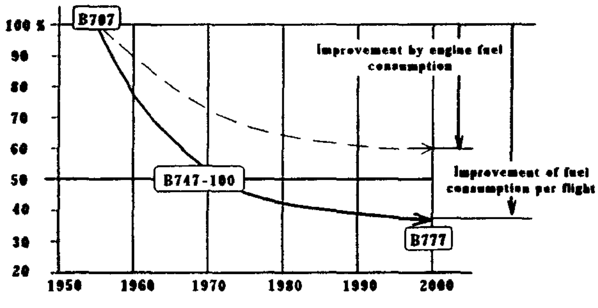

Fig.1 Improvement in Aircraft Fuel Consumption

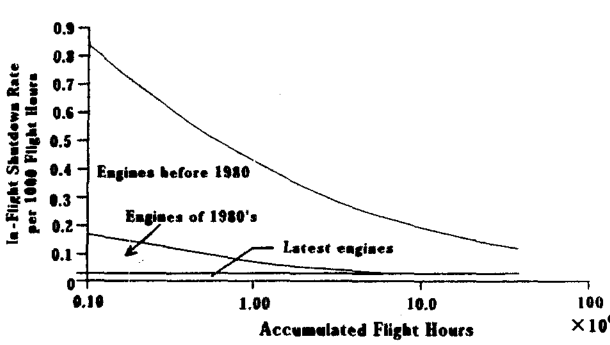

Fig.2 Improvement in In-Flight Shutdown Rate

and show growth rates of around 5% in passenger traffic and even higher rate for freight traffic (see Fig.4).

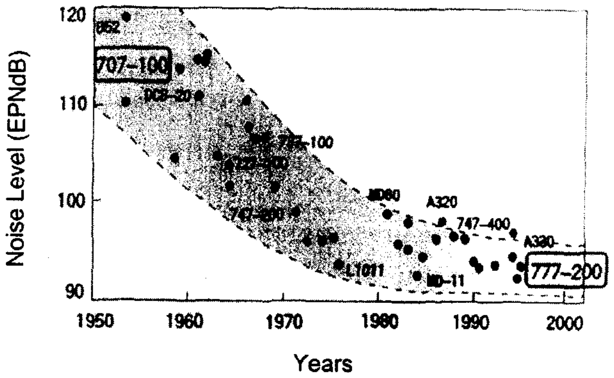

Fig.3 Trend of Aircraft Noise Level

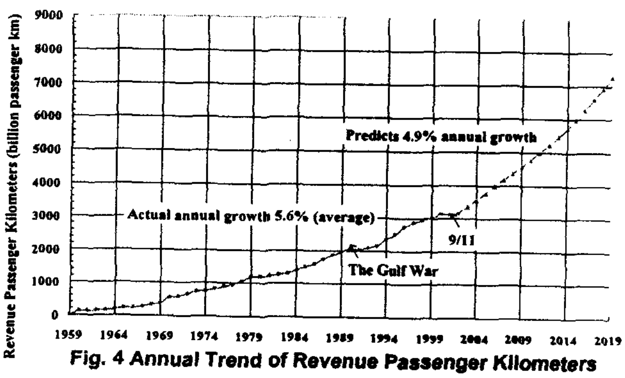

Fig. 4 Annual Trend of Revenue Passenger Kilometers

Japanese industries and research organizations also came a long way, with the manufacturing of the licensed engines commenced in late 1950's, national research programs in the 1960's to 1970's and the international collaborations for the civil transport engines from the 1980's and, it may be appropriate to say that Japanese industries are now playing important roles worldwide in the highly competitive aircraft industries.

2. Efforts and Status in Japan

As for the propulsion system for the civil transport, major research and development activities in Japan started in the 1970's when the national project for the FJR710 engine, the research turbofan of 5 ton thrust class, was launched. This successful program led us to the international collaboration program for RJ500 and then, V2500 engine in the 1980's. V2500 program was really a challenge at that time, as we formed up a Joint Venture, IAE, with RR, P&W, MTU and Fiat, participating in every aspect of the business, from design/development of the engine, sales to product support. With these experiences, Japanese industries then started to participate in most of the commercial engine programs in the world, such as GE90, Trent, PW4000 and CF34 as risk and revenue sharing partners (see Fig.5). In the case of CF34-8, -10 engines for the regional aircrafts, program share is 30% including the responsibility of core engine portion (HPC). In the significant market segments in the next 20 years, we are expecting to see the following involvements of Japanese aero engine industries;

Engines for Large Twin (Such as B777)	: 10% Program Share
Engines for 200-250 Pax Twin	: 15-20%
Engines for 130-180 Pax Twin	: 20-30%
Engines for 50-100 Pax Regional	: 30-50%

In parallel with the above-mentioned product developments, various research programs have run under the co-operations of research institutes, universities and industries (also see Fig.5). It is also to be noted that there have been active government

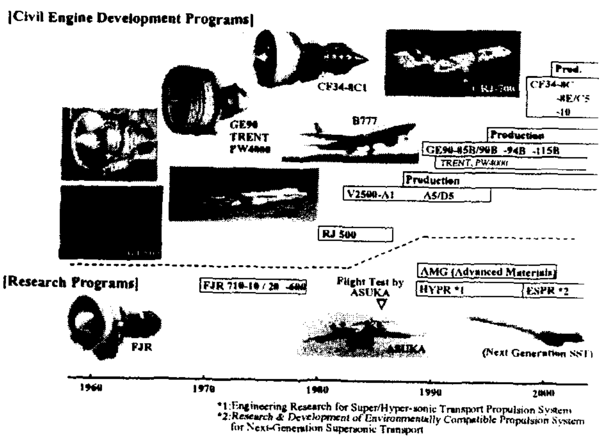

Fig. 5 Research and Development Activities in Japan (Civil Engine)

engine development programs such as for the trainer aircraft and the patrol aircraft, which have contributed a lot to the development of the technologies covering the whole engine.

In the civil air transport business, the Maintenance, Repair and Overhaul (MRO) activities are now of great concern and importance both for airline operators and the maintenance providers (engine OEM's and independent shops). Japanese industries have made challenges in this field and are now becoming one of the significant players, especially in the MRO of medium-to-small engines. (see Fig6).

Having described the above, it is also well recognized that more efforts and more challenges will be required if we try to continue and enhance our roles in the aero industries.

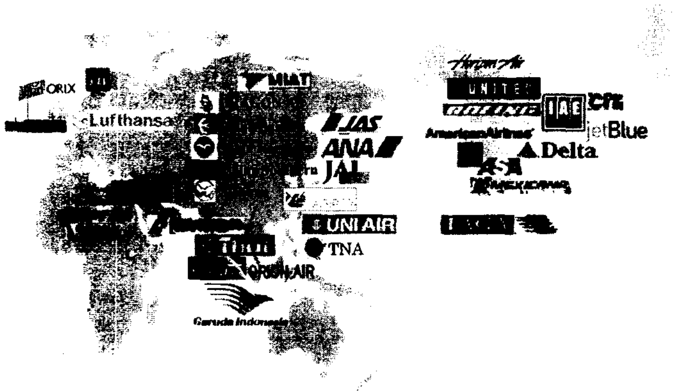

Fig. 6 IHI Engine Maintenance Activities: Global Customers

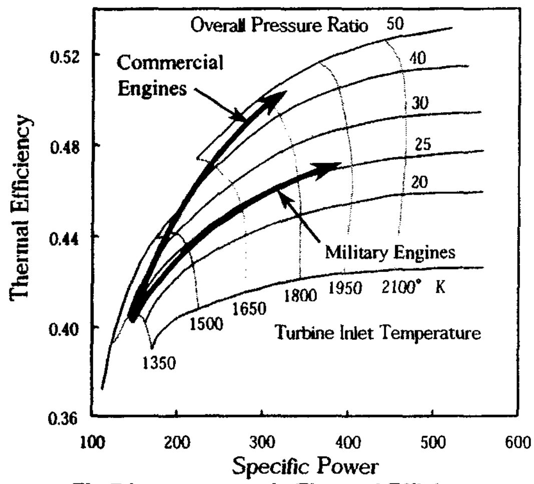

Fig.7 Improvement in Thermal Efficiency

3. Challenges in Technologies

It is no doubt that the technology has been the key factor in this field and it is interesting to look forward and attempt to identify what will drive the aero engine industries forward in the next 20 to 30 years.

3.1 Fuel Consumption

Engine specific fuel consumption (SFC) can be related to the cycle efficiency parameters as follows:

$$\mathrm{SFC} \propto \frac{V_0}{\eta_{th} \cdot \eta_{prop}}$$

, where V_0 is the flight speed, η_{th} is the thermal efficiency and η_{prop} is the propulsive efficiency . For a turbofan engine, the thermal efficiency is largely determined by the overall pressure ratio (OPR), the turbine inlet temperature (TIT) and the efficiency level of individual components such as compressors and turbines. Fig.7 shows how thermal efficiency relates to OPR and TIT at a constant component efficiency level, with the trend of civil engines and military engines, which indicates that the thermal efficiency is now reaching 50%, but is being saturated. This phenomenon is mainly due to the turbine cooling flow increase to cope with a higher TIT and the higher temperature of the cooling flow itself when OPR is increased.

Fig.8 tries to show how cooling flow or cooling technology contributes to fuel consumption. With the current level of cooling technology, optimum SFC goes with OPR of around 40, while SFC is becoming better by 4% if cooling flow can be reduced by half. If turbines that do not require cooling are realized by the technology advances such as composite materials, about 7% of SFC benefit is expected with optimum SFC at a higher OPR. This is one of the reasons why materials and cooling technologies continue to be important and require challenges.

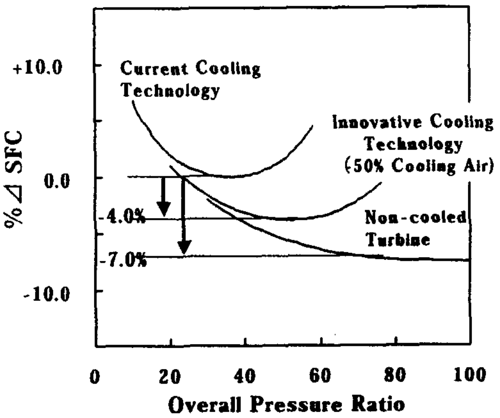

Fig.8 SFC Improvement by Cooling Technology

Component efficiency levels have a direct effect on fuel consumption, and remarkable strides have been made over the last 50 years with most of the turbofan components now achieving polytropic efficiency levels in excess of 90%. The emergence of accurate CFD design codes, that can analyze an entire multi-stage compressor or turbine, have now enabled the 3-dimensional aero-dynamics to be addressed. The aggressive challenge to control the secondary flows through the turbo-machinery will deliver a few more increments of component polytropic efficiency, which will potentially improve the SFC by 4 to 5% in the next 20 years.

Improvements in propulsive efficiency arise largely through increases in bypass ratio (BPR), or reduction in specific thrust (defined as the ratio of net thrust to total engine mass flow). BPR has increased from 1 or 2 in the 1960's to 5 or 6 in the 1970's and 1980's, while new engines for wide-body aircrafts in the 1990's typically have BPR in the range of 7 to 9. It should be noted that increases in BPR were made possible by powerful core engines with higher TIT and OPR. Further increases in BPR are still possible and are likely, but will only benefit aircraft fuel burn if ways can be found to minimize the increases in weight and drag associated with larger fan diameters. Here, utilization of high-strength, light-weight composite materials can play an important role and will be area for challenges.

3.2 Key Technologies in Turbo-machinery

Aircraft engines, as a typical and successful turbo-machinery, have achieved significant improvements in performance, reliability, maintainability and life in these 40 years. However, because of the ever-demanding design requirements and the very severe operating conditions and environments, it is true that there are problems in the field, which are sometimes highlighted especially when they relate to a safety concern.

Shown below is the list of problems we typically see in the field and of the difficulties we typically have in the design and development phase:

- Oil leaks and Bearing problems
- Vibrations (part level to engine level)
- Thermal distress (such as crack or life shortage)
- Wear, deflection/distortion
- Instabilities such as stall or control-related problems
- Over-temperature (less margin, control-related)
- Design to Blade-out (development phase)
- Design to Icing (development phase)

In order to address those problems and difficulties in more intelligent manners, technology developments are active in the industries, which are expected to help providing more economic product with least surprises, less maintenance work, and in a shorter development cycle.

Value of CFD analysis as a design tool is now significant with its modeling techniques and the capacity continuously enhanced. Unsteady 3-D CFD tools are now used to analyze multi-stage compressors and turbines for the accurate simulation of performance and to analyze the flow instability. As the engines with less stages and less number of parts

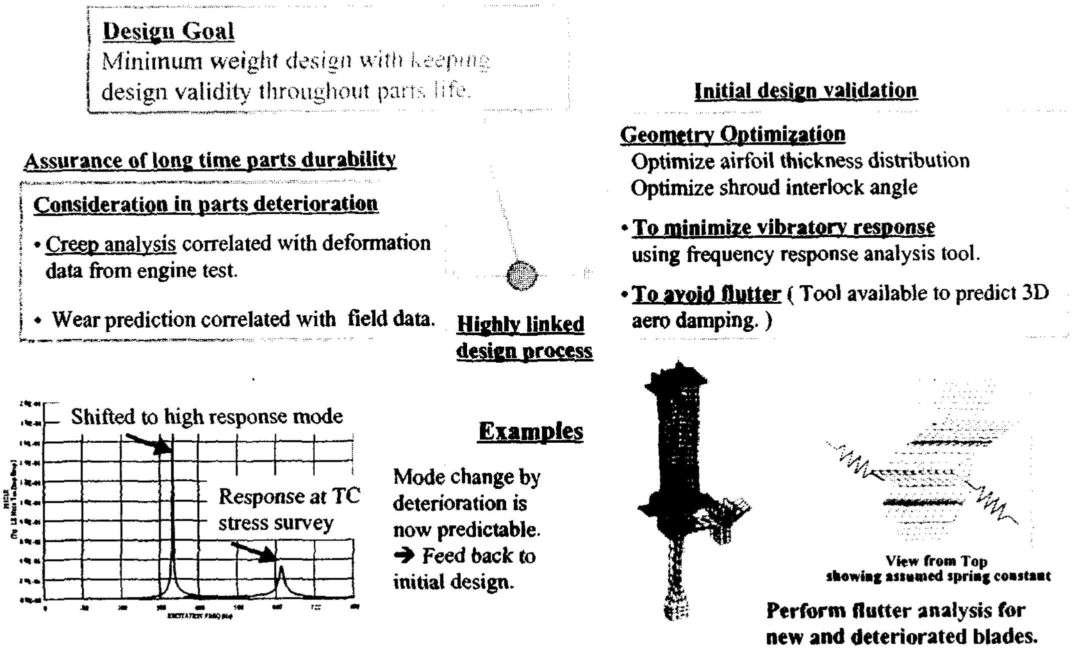

Fig. 9 Advanced design process developed for LP Turbine Blade

(airfoils) are being requested for the reason of lower cost of ownership, CFD analysis tool that can validate the stability margin is becoming important.

When the unsteady CFD analysis is combined with the airfoil vibration/stress analysis, it represents a very useful design tool for airfoils in the turbo-machinery, where there is always a strong request for weight reduction (thinner blades and vanes), which tends to push airfoils toward the risk of flutter or other vibrations. Fig.9 shows the recent design practice for LP turbine blades, where careful aero-mechanical analysis is conducted even considering the creep deformation and the wear at tip shroud in the service life.

CFD tool is also being used to analyze internal rotor cavity flow or internal cooling flow. The results are then used for the heat transfer analysis and for the thermal analysis of disks, seals, shafts in order to evaluate the stress, deformation of those parts, which then enables us to validate or adjust the clearances between the seals. As the internal flow balance changes when seal clearances change, this requires an iterative design effort. Challenges to establish comprehensive analysis tools for this iterative design process is underway, as heat transfer and clearance design have been really key design areas for the turbo-machineries and, if this advanced analysis tool is in hand for us to quickly predict temperature, stress of the parts and critical seal clearances (flow balances) at any engine operating conditions in a reliable manner, the risk of the problems mentioned above such as oil leak, crack and life shortage will be significantly reduced.

Airworthiness requirement regarding Fan Blade-out is an unique and stringent requirement to the aircraft engine design and, with a big fan blade in a high BPR turbofan, is very demanding to most of the engine structural parts. The impact on engine weight is so significant that various means of reducing the dynamic load have been developed, such as "Fuse Bolts" concept. Comprehensive dynamic simulation tool is also valuable here to help validating the design and to avoid the last moment surprise in the engine certification program.

3.3 Technologies for Environmental Compatibility

As the noise regulation is getting stringent from Stg.3 to Stg.4 and local rules or constraints are imposed in the specific airports in the world, acoustic emissions are becoming increasingly important factors in the engine design, being traded-off with performance and weight. Key noise sources are from the exhaust jets, turbo-machinery (mainly the front compressor stages and the rear low-pressure turbine stages) and from the large fan. With the intensive research efforts in these 30 years, various means to address those noise sources have already been incorporated in the engine design, such as reducing jet velocity, optimizing the bypass to core jet velocity ratio, introducing devices for the controlled mixing between the jets and through careful choice of airfoil numbers, rotor-stator gap increase. Acoustic linings are playing important roles to reduce noise as well.

In order to accurately predict the noise level of the engine, which itself is very important to the product development, and to further reduce noises, technology developments are very active in the world. Fig.10 shows one of the directions in technology, indicating that noise sources and the power levels in the actual engine can now be precisely predicted by using 3D unsteady CFD analysis and, with more powerful CFD tools in the near future, it will become possible to analyze the noise propagation inside the engine and to the environment.

As for combustion emissions, most of modern engines easily meet the regulations, except for NOx. This is because the production of NOx in the combustion chamber is largely a function of local (peak) temperature. Thus, the drive to improve fuel efficiency through OPR and TIT increases conflicts with low NOx production. As the ICAO regulations become tight and even more stringent local rules are imposed in some countries with the penalty of additional tax, technology developments have been active in this arena. In the 1980's to 1990's, sophisticated staged combustors, which reduce NOx

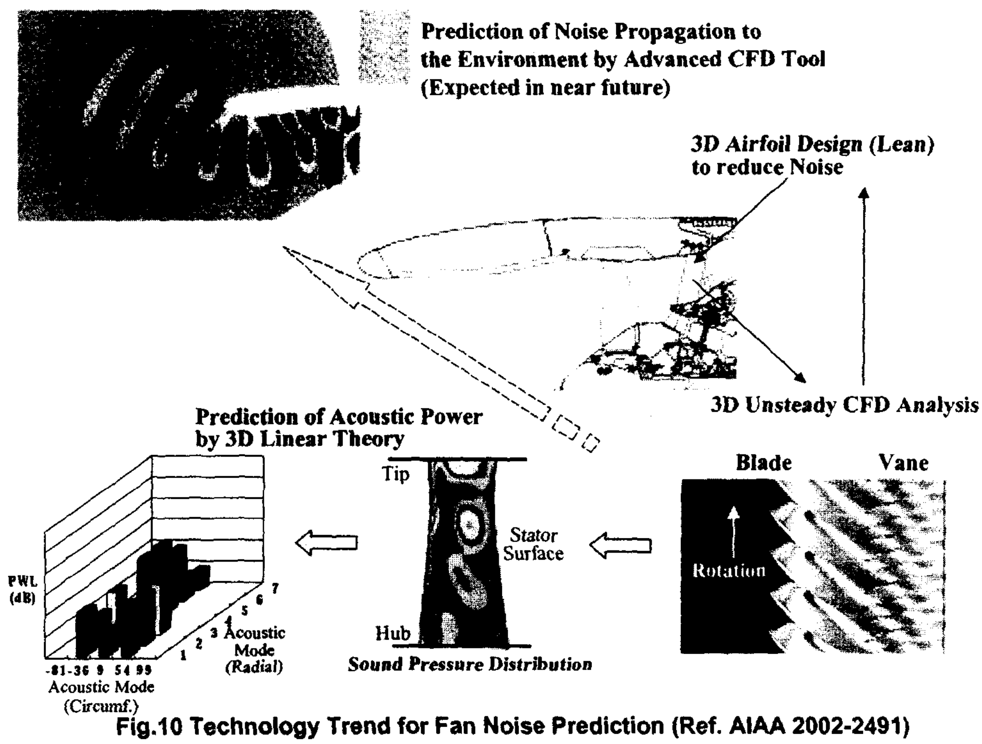

Fig.10 Technology Trend for Fan Noise Prediction (Ref. AIAA 2002-2491)

by splitting the combustor into two chambers, each optimized for low and high power operation, were introduced in some engines. Combustion researches now centers on achieving lower NOx by improving the mixing of fuel and air prior to entry into the chamber, through pre-mixing or pre-vaporization, which reduces peak combustion temperature. This has also been one of the key technologies for the next-generation supersonic transport.

3.4 Challenges for New Evolutions

As people continue having dreams of flying higher, faster and safe with comfort like a bird, challenges are always there to develop new aircraft and propulsion system concepts. And, new concepts usually require new evolution of technology developments. When "Sonic Cruiser" was proposed a few years ago, intensive study for the propulsion was conducted to manage or reduce noise against the increase in specific thrust (higher fan pressure ratio). Contra-rotating fan was thought to be a longer-term option for that sort of aircraft concept, along with intensive use of composite materials for the weight reduction. Recently, program for new subsonic aircraft, B7E7, is being launched, which aims at reducing aircraft operating cost by 20% and adopting "All Electric" or "More Electric" concept. This forces the propulsion system to challenge to higher OPR, higher BPR, a percent or more of efficiency improvement in each component, as well as to the efficient gear drive system to power huge generators without any impact on fuel burn or operability. Aggressive weight reduction efforts are also required to achieve this goal.

What is beyond those is an interesting question. There have been a lot of research activities for the next-generation supersonic transport, which requires some more technology developments before going into the product development phase. Blended Wing-Body (BWB) concept can offer a step improvement in fuel burn, addressing the global warming concern as well, where ultra-high BPR engine is expected and may be installed on the wing. Besides the civil transport application, there will be good opportunities for BWB to be applied for freighter and military transport.

Changing the viewpoint, concept of maintenance-less aircraft or engine is recently talked about, somehow compared with automobiles. It is understood that this concept is discussed from time to time, as an ultimate goal; between the people concerned. However, the realistic approach in the next decades is believed to be "less-maintenance just as planned", which requires significant technology challenges in reality.

4. Challenges in Business

As stated above, civil aviation will continue growing and the market opportunities will be there. Technologies no doubt continue to be the key in the aero-engine industries, where many engineers love to challenge them. Then, what are the difficulties for us in pursuing business opportunities for further step-up? And, what can we or should we do to challenge to those difficulties?

4.1 Difficulties

First thing we should recognize is that 3 major OEM's, GE, RR, P&W, do have significant market shares in the aero engine industry and continue making efforts to develop technologies and to enhance the relationship with airline customers. This is the fact rather than difficulty and, without a partnership with major OEM's, business opportunity will be very limited in this highly global business.

Another important aspect of the aero-engine business is its huge investment for the product development and its historical business structure where it takes 15 to 20 years to recover from this investment even if it is successful (see Fig.11 for the typical cash flow curve). Japanese aero-engine industries have spent more than $2B for the international collaborative product developments such as for V2500 and CF34 engines in these 25 years and it will take another 15 to 20 years to recover. We are deep in negative side, yet we have to invest further for the next programs.

It should also to be noted that the aircraft industries in the world have more capacities than the market requires right now. Current players including various manufacturing sources in the world certainly want to continue and enhance their businesses while new participants are always seeking for their chances. This means the severe competitions on the global basis, in terms of engineering, quality, cost and speed, which is making it more difficult for everyone to recover from the investments.

Furthermore, because of the nature of this industry, customer support network on the global basis is important, which requires significant investments, resources and innovations. This will certainly be another difficulty that new challengers will face with.

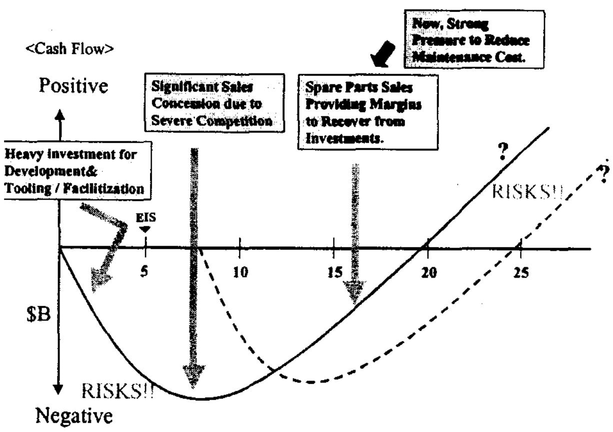

Fig.11 Typical Business Cycle of Aero-Engine Industries

4.2 Challenges

The first thing we have to do is to be more competitive for the current products and for the near term projects. This in effect defines the "Present Value" of that company or business unit. As it is usually impractical to be competitive in every kind of parts, modules of engines and in every design/engineering field in these days, one practical approach may be to become "Number 1" in the world in some components. Center-Of-Excellence (COE) concept is sometimes used to explain this approach where technologies/engineering excellences have to be in the core and manufacturing forces and design teams are well integrated to produce real values for the customers. This is not easy, but without this kind of efforts, there will not be a way ahead.

What is important in parallel is to increase "Expected Value" or "Future Value" of the business unit with minimal investment. In the civil aero-engine industries, there have been several cases, especially in U.S. and Europe, that the technologies developed in the advanced government engine programs contributed to the next generation civil products. There have also been various research programs supported by governments, where technology demonstrator engine programs were very valuable in transferring those technologies into the products. Now, the situations surrounding each government and our industries have changed a lot, and it is getting fairly important for us to focus on "Expected Value" as measured in the world-wide competition when we challenge to advanced technologies. On the other hand, in order to properly understand the value to the customers of certain advanced technology, we have to know the engine as a system and the business structure. Because of this fact, i.e. in order for us to be able to evaluate the value by ourselves, any opportunity to design/develop our own engine, for government programs or for research demonstration, is still so important.

As already mentioned above, value to the customers is the key element as in any business nowadays. In the civil aviation industries, number of customers (airlines) is a few hundreds who have excellent expertise and have accumulated a lot of experiences of operations. Therefore, to listen to the voices of airline customers at any opportunities is very important. Yet, it is not straightforward as major OEM's primarily have the customer support networks. Therefore, efforts are to be made, for example, by participating in those customer support networks and by challenging to the engine services business worldwide, both of which certainly require another investments and resources. As these efforts place us much closer to the customers, they will also contribute to improving the integrity, flexibility, responsiveness of ourselves and the business units.

5. Conclusions

There has been remarkable progress in the aircraft propulsion system in the last century, and the technologies and the industries have been reasonably matured. On the other hand, aircraft and its propulsion system no doubt continue to be the frontiers in this new century, that require significant technology challenges. Aero-engine industries have been very international and will see more dynamic partnerships, consolidations, business structures on the global basis in the coming years. No boarders or boundaries.

In such a situation, as a challenger from Japan or from Asia, let's think about and talk about how each of us can be contributing more to producing values, and let's energize each other in all the associated organizations towards concerted efforts or co-operations.

There are many exciting challenges ahead.

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