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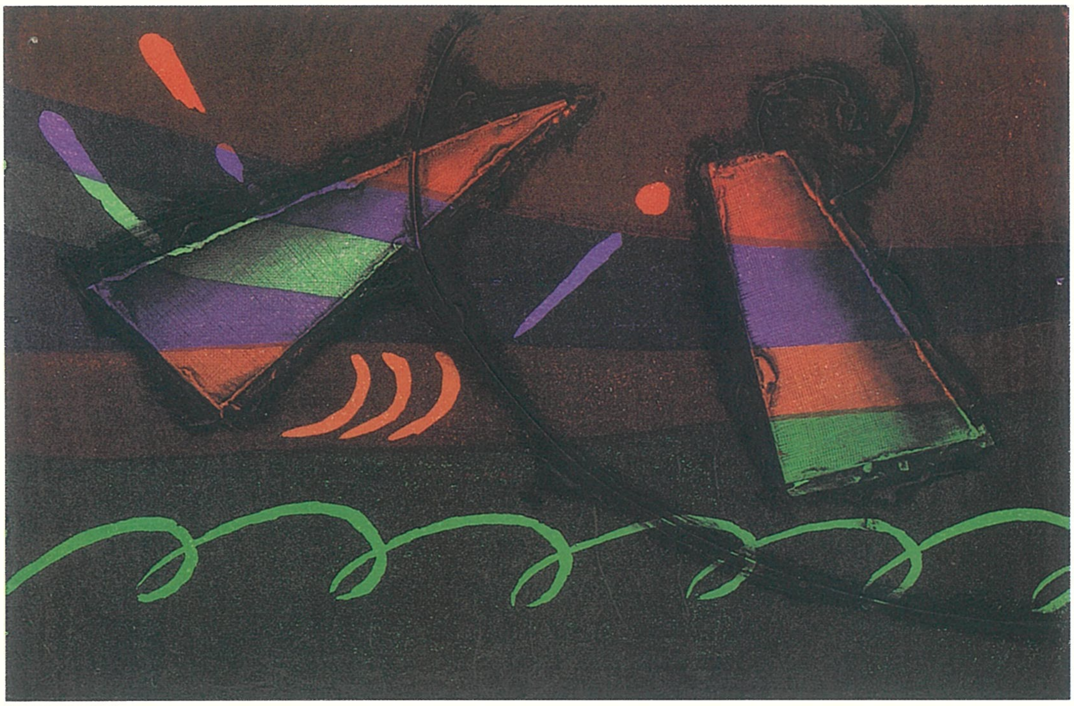

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SPECIAL ISSUE
SPACE TOURISM PART TWO

THE JOURNAL OF SPACE TECHNOLOGY AND SCIENCE

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A Special Issue of the Journal of Space Technology and Science : SPACE TOURISM PART 2

FOREWORD

It is a special pleasure for me to write this foreword for two reasons. Firstly, all the papers included in this issue have been presented at the Nineteenth International Symposium on Space Technology and Science (ISTS) held in Yokohama during May 15 - 24, 1994 for which I served as Chairman of the Organizing Committee. Since the first meeting was held in 1956 by the Japanese Rocket Society, the ISTS has provided Japanese domestic researchers in the field of space technology and science with one of few opportunities to exchange information in Japan on an international basis. Recently, the symposia have been held every two years at nationwide locations, incorporating local events and improving the program arrangement. A new feature of the nineteenth meeting was the first attempt by the program committee to hold one evening poster session. Fortunately many papers have been presented at that session, and lively discussions between presenters and attendees, partially augmented by a refreshment service in the session room, satisfied the program committee members and myself. In selecting papers to be published in the Proceedings, the program and publication committees of the symposium determined that all the papers presented in the space tourism corner of the poster session should be included in a volume of JSTS as proposed by the authors. One of the authors, Prof. Nagatomo, was be assigned to be Guest Editor for this issue.

Secondly, it was during my presidency of the JRS that the topic of space tourism was formally adopted by the society as an important research subject for the future of rockets. In my speech welcoming the proposal of a space tourism study at the JRS annual meeting of 1993, I introduced my view on Japanese involvement in manned spaceflight. Until the recent political decay of the Soviet Union, everything seemed good for the two space super powers; U.S. and USSR, and I thought that Japan could rely on them for manned space technology. In fact, Japanese space policy was following in the same direction. However, things have changed, and I am changing my view on our manned spaceflight. Learning the achievements made by US and USSR, we have to contribute to future manned flight in a different way. Space tourism should be a direction of our efforts. Thus, I completely agreed for the JRS to adopt space tourism as the main topic of its research. I am very much interested in this publication, since it is considered as an interim report on the research.

Although our society is small and this publication is not very widely distributed, we have contributed to strengthening international relations in space activities, for example, by participating in the first ISY meeting held in Hawaii in 1988. Hoping that space tourism will open a new era of spaceflight for mankind, I am looking forward to hearing opinions and suggestions on this special issue from you.

Ryojiro AKIBA
Chairman of 19th ISTS, Yokohama, 1994
Director-General of ISAS
Past JRS President

September 15, 1994

EDITOR'S NOTE

This issue is the second special issue featuring space tourism. Readers will see that this issue is an exact follow-up of the earlier one which was published as the spring issue in 1993 (vol. 9, no. 1) . However, the background of this publication is different from that of the first one which was intended to summarize a panel discussion of the Japanese Rocket Society. By contrast as introduced in the foreword by Dr. Akiba, this issue features by papers presented at the 19th International Symposium on Space Technology and Science held in Yokohama from 15th to 24th of May, 1994. The topic of space tourism was not familiar from past ISTS sessions. Therefore, when the program committee received several papers on this subject, I was consulted by the committee members on how best to fit these papers into their session plan. After a brief discussion, it was determined that all the papers relating to this topic would be accepted for the poster session. The result was very successful. The audience had a chance to listen to and discuss with the presenters on space tourism and to familiarize themselves with various aspects of this new topic walking back and forth to see the different posters arranged side by side. Thus the presenters had the best audience. Among them were the DC-X program manager, Dr. Gaubatz and the author of the BETA reusable vehicle Dr. Koelle.

The five papers included in this issue are based on the ISTS preprints prepared for presentation at the poster session by permission of the conference. The original preprint number is given in a footnote on the first page of each paper. The editor has changed the order of the papers from the order of the preprint numbers. As the result, in this volume, the first and second papers are concerned with market research and tourist service, respectively, while the other three papers are technical outputs of the JRS transportation research committee chaired by Kohki Isozaki.

ACKNOWLEDGEMENTS

On behalf of the authors of the papers included in this volume, I would like to express our thanks to the committee members of the 19th ISTS, Yokohama, 1994, and especially to Dr. Akiba for kindly writing the forword, and Prof. Tanabe for kind arrangement of our papers in the ISTS program, and generously accepting our offer to publish our papers in this issue of the JSTS. I would also like to express my personal appreciation to Prof. Ohkami, Editor-in-Chief of the JSTS for providing me with this second chance to edit a special issue on space tourism. Finally I must thank all the authors of the papers included for their cooperation with my editing work.

Makoto Nagatomo
Guest Editor
JRS Vice-President

COMMERCIAL IMPLICATIONS OF MARKET RESEARCH ON SPACE TOURISM[+]

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Abstract

During the summer of 1993 a market research questionnaire designed to investigate the potential demand for orbital tourism was completed by more than 3000 people from all age groups in Japan - the first such market research in the world. Using the results of this survey, a number of analyses are being performed. From the prices that people say they would pay to visit space, a demand curve can be derived, showing the level of demand that could be expected at different price-levels. The possible pattern of demand growth as the range of commercial space tourism services grows is also considered. The level of investment in the development of reusable passenger-carrying launch vehicles that could be commercially justified by this market is also estimated, and the assumptions made are discussed.

1. Introduction

In the post-Cold War era, the justification for the space industry to continue to receive the large government budgets on which it has depended to date is being questioned. In particular, the value of government investment in the development of new launch vehicles when there is over-supply in relation to the world-wide launch rate of just a few tens of launches per year is questioned. Yet in the absence of a new generation of fully re-usable launch vehicles with much lower launch costs than today, the space industry has little possibility to grow into a commercially profitable and self-sustaining industry. Justifying such investment will require the development of new launch markets which have the potential to grow to traffic rates many times greater than the present limited demand for satellite launches.

One possible source of demand for future launch services, and so of future revenues and profits to finance the development of re-usable launch vehicles, is tourism - the making of short visits to low Earth orbit by fare-paying customers. In the modern world tourism represents one of the largest, most international industries, and it is growing fast, particularly in the more economically advanced countries. Furthermore, space travel has a high level of popularity among the general public. The desire of many people, particularly the young, to explore the unknown world of space and face new challenges seems likely to create growing demand for popular space travel. Thus it seems possible that the commercial demand for space tourism could be very high, and that the widespread desire of humankind to have the experience of going to space for themselves could become a driving force for the space industry in the future.

However, the attractiveness of "space tourism", or "orbital tourism" (at least in the early stages), as a potential target market for commercial companies will depend critically on the actual scale of future demand for space tourism services at different prices. To date very little data has been collected on this subject in any country. During the summer of 1993 a market research questionnaire on the potential demand for orbital tourism was completed by more than 3000 people from all age groups in Japan. The questionnaire was distributed face-to-face mainly in large companies, universities, schools, obtaining a response rate of well over 90%. Details of this survey, and initial results have been published in (Ref. 1), but the idea of space tourism was very popular. Nearly 80% of those

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[+] Presented at the 19th International Symposium on Space Technology and Science (ISTS Yokohama), 15-24 May, 1994. The original preprint number was ISTS 94-g-21p.

under 50 said that they would like to travel to space, and 45% of those over 60, with no significant difference between the 1465 men's and 1565 women's answers. Some 70% of those who wished to travel to space said that they would pay three months' salary or more, and the great majority said that they would like to stay in orbit for a few days. In the following we discuss some further details of the results.

In considering whether a new service such as passenger flights to Earth orbit could become a profitable business, companies must estimate both the costs that they would incur in providing the new service, and the revenues that they could earn. The costs depend on how low engineers can reduce the manufacturing and operating costs of re-usable launch vehicles, and the revenues depend on the size of the potential market for the service, that is on how popular the service could become. Consequently in order to assess the feasibility of this business we need to do both engineering and market research. Currently the Japanese Rocket Society is studying the engineering and other aspects of space tourism in its Space Tourism Study Program (Ref. 2). The authors of this paper have been carrying out preliminary market research.

2. Limitations of market research

In principle, if firm data were available concerning the future demand for space tourism at different price levels, it would be possible to plan a business to provide such a service, provided that the vehicle costs could be reduced sufficiently. In practice, however, any conclusions that can be drawn from market research data on this subject can be only tentative, for a number of reasons. First, the reliability of all market research concerning future products and services is inherently limited. There have been many cases of new products' sales being very different from the results of market research, both greater or less. This is due fundamentally to the impossibility of predicting the future, and more particularly to peoples' inability to foresee their own future behaviour accurately.

Second, this uncertainty is particularly strong in the case of a new and futuristic service such as space tourism about which peoples' expectations are particularly likely to be mistaken. Thus the reliability of market research results must be more uncertain than usual. This is not to say that the results must be inaccurate, but rather that it is not possible to know how accurate they are.

Third, it is uncertain how representative the market research data that have been collected are of the Japanese population as a whole. The authors tried to ensure a wide distribution to people outside the space industry. As discussed in (Ref. 1), by distributing the questionnaire on a face-to-face basis, the response rate was nearly 100%, which avoids the common bias of receiving answers only from those who are interested in the subject.

There are nevertheless some biases in the results. For example, 64% of Japanese households are salaried, and their income is some 5% above the average, while 36% are self-employed and their income is some 10% below the average, but only 2% of the participants in our survey were from the self-employed population. However the proportion of self-employed participants who said that they would like to go to space was not very different from the self-employed, 77% versus 81%. Consequently, while recognising this limitation in the survey, it was not felt necessary to correct the data as a result.

Fourth, it is uncertain how representative our data are of the populations of the advanced industrial countries as a whole. Although similar market research has not been carried out in these countries, the market for space tourism seems sure to be international. Consequently, in order to understand the true potential market we need to consider at least North America, Western Europe and Australasia as well as Japan, the total population of which countries is some 6 times that of Japan.

There may be significant differences in demand between these countries due to the cultural differences between them, which are significant. But there are also important common strands in modern popular culture. Science fiction and particularly space fiction, international organisations such as the Young Astronauts Club, and the world-wide popularity of big-budget space-related films such as "2001" or "Star Wars" suggest that people in many countries enjoy these ideas. Thus, although it is possible that Japanese people are more interested in space travel than other countries, it seems likely that such an interest is also widespread in America and Europe.

However, there are also significant differences between Japanese consumer behaviour and that of Americans and Europeans. One difference is the much higher savings ratio in Japan (which is related to the low interest rates, the high rate of investment, and the low level of unemployment in Japan). Because of their high savings, typically amounting to one year's income held in financial assets, Japanese are able to spend relatively large amounts on things that have particular value for them, such as education, weddings, foreign travel. Another difference is the relatively equal income distribution in Japan compared to America or Europe. From this we might guess that demand for space tourism services may be higher in the latter countries while the price is so high that only the rich can afford it, but may be relatively greater in Japan if the price is low enough to become affordable by a large proportion of the population.

Fifth, since the number of people who said that they would pay one year's income or more to go to space was considerably fewer than those who said that they would pay less, the figures must be considered statistically less reliable. That is, a small number of unrepresentative answers could bias the results significantly. Likewise, the 3 - 4 % of non-student participants in each age-group over the age of 20 who said that they would pay 3 years' or 5 years' salary for a trip to orbit may be unrepresentative, so that the proportion of people with similar opinions may be significantly less than this. Even so, and even if these people are wrong in the sense that in the event of such a service becoming available many of them would not actually pay such a high price, we must still recognise that for a significant number of people the idea of going to space is clearly a powerful dream. However, although there may well be significant demand for space tourism even at very high prices of more than 10 million, this will probably be mainly from uncommonly rich people, rather than from people with average incomes paying a multiple of their annual salary. Consequently, in analysing the results we have included these multi-year answers with those who said that they would pay one year's salary.

Despite these limitations of our market research data, it is nevertheless interesting to use the results as a basis for estimating the future demand for space tourism services. Indeed we have no choice but to do this if we are to develop a successful commercial service. We must also remember a fundamental difference between scientific research and business. Businesses do not require proof before they invest in a project, but reasonable probability. Investment entails risk because the future is uncertain. Businesses that wait for proof risk being beaten by bolder competitors.

3. Demand curve

Initial results of our survey are described in (Ref. 1). For the present analysis, in order to derive a demand curve for space tourism, we excluded teenagers, as lacking experience about financial matters, and those over 70 years old, as being unlikely to travel to space. By making the assumption that the participants in the survey are representative of the Japanese population as a whole, we can estimate the proportion in each age group who say they would pay each price, in terms of months of salary. National income statistics allow us to estimate the monetary value of the monthly salaries for different age groups. By using national population data broken down by age we can then estimate the total number of people in Japan who would go to space at different prices.

In order to estimate the number of people who would travel to space each year, we need to develop a traffic growth model, and we plan to do this in the next phase of our analysis. For the present, in order to obtain a single figure representative of a future space tourism business, we simply divide the total demand by 25, that is we assume that 4% of those who wish to would go to space each year. Figure 1 shows the results of this simpler case with an exponential curve fitted.

At first sight the demand shown in Figure 1 seems very high. For example, at prices of ¥5 million and ¥2.5 million the demand figures of 100,000 and 500,000 passengers per year are some 10 - 20 times higher than the estimate published by Citron in 1985 of 5,000 - 10,000 passengers per year at a price of $50,000, and 20,000 - 50,000 passengers per year at $25,000 (Ref. 3). However, in order to compare these figures accurately we need to make some adjustments. First we should adjust the earlier figure for inflation from 1985 to 1993, which reduces the difference to some 5 - 12 times for the lower price. If we further adjust the figures to use a "purchasing power parity" exchange-rate between the yen and dollar, which is arguably more appropriate for comparing consumer prices between Japan and the USA, the difference falls to perhaps 3-7 times.

However, Citron also proposed that demand at a price of $25,000 might grow as high as several million passengers per year (Ref. 3). Thus, though demand in Figure 1 is greater at higher prices, the demand at lower prices is less, since it shows demand in excess of 1 million passengers per year only at prices below ¥1.4 million ($14,000). But the results are also incompatible in a number of ways.

The earlier estimates were for world demand, whereas the market research data was from Japan alone. The earlier data relate to just a trip in a launch vehicle, whereas a large proportion of the market research data represents people who wish to stay a few days in orbit. Finally the earlier estimates included projections of growth over the next 30 years, whereas the market research data has no explicit time-scale.

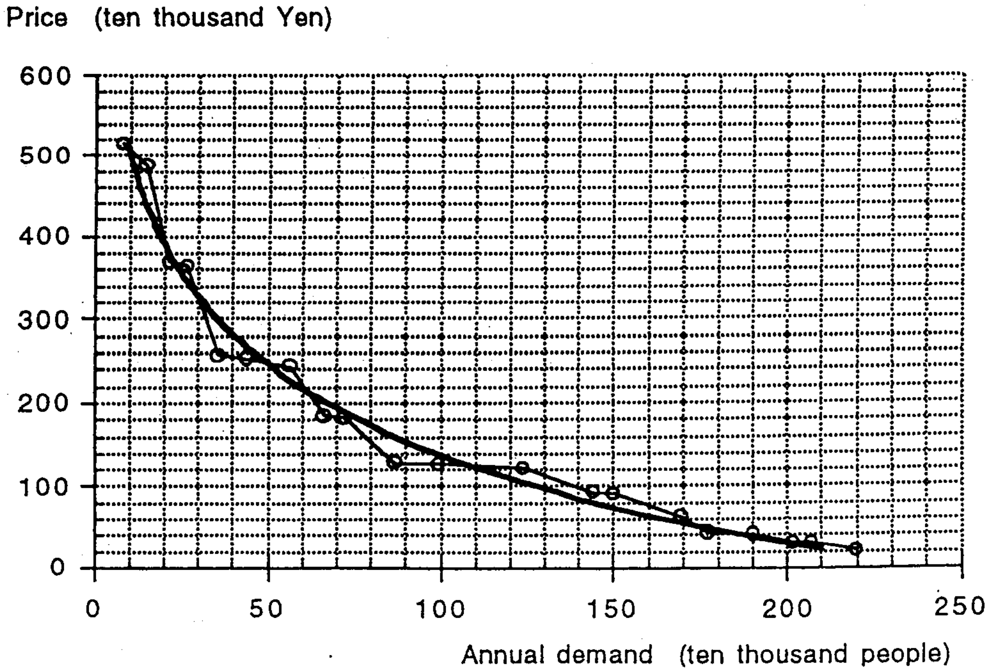

Figure 1. Potential demand curve for space tourism services.

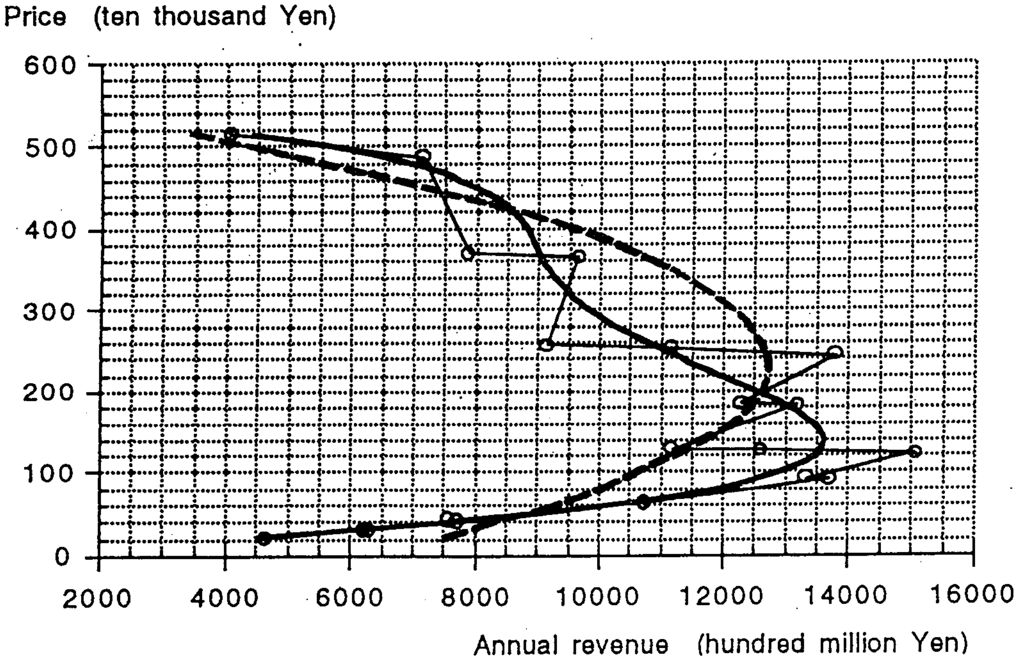

Figure 2. Potential revenue curve for space tourism services.

Based on the data in Figure 1, Figure 2 shows the annual revenue that would be earned at each price level, with quartic (solid) and quadratic (dotted) curves fitted. Annual revenues reach a peak of some ¥1.35 trillion ($13.5 B), though there is some uncertainty about the price at which the maximum revenue would be earned. In the smoothed curves it lies between ¥1.2 million and ¥2.4 million. The correct figure will in practice depend on the different services that are offered, as discussed in the following section, but which are not distinguished in Figures 1 and 2.

Since these figures seem very high, it is interesting to consider possible reasons for discounting them. It might be argued that for the various reasons discussed in the previous section these figures should be discounted by a factor of 5 or 10. To discount them even further, to perhaps 1/20 of the market research data, seems excessive: In a country where many people pay three months' salary for a foreign holiday, it does not seem unrealistic to expect that many would pay the same or more for a trip to space, which is clearly a particularly popular dream.

Alternatively it might be argued that once it became a commercially available service, space flight would lose its glamour, and so people would find the reality less attractive than the dream today. While this argument probably has some value, on this qualitative level it is possible also to argue the opposite: that in the coming years, a visit to orbit to see the Earth from space and to experience living in weightlessness could become the defining experience of the new post-cold-war era, in which advanced technology will be used for peaceful more than for military purposes, as foreign air travel might be said to have become in the late 20th century. In addition, the marketing industry, which grows ever more influential with the spread of the mass media, would surely be pleased to be offered the challenge of keeping the idea of space travel exciting. In view of its existing popularity, and of the almost limitless range of interesting future entertainments that can be developed in orbital facilities (Refs 4, 5) and beyond, it does not seem a serious danger that space tourism might fail through being considered boring.

Another possible response is to say that the survey is unrealistic because low-cost, airline-type launch operations are not feasible. Although this has been the opinion of many in the space industry over the past quarter-century, the tide of opinion is now changing. Hudson's work on SSTO VTOVL vehicles (Ref. 6), which had been largely ignored through the 1980s, has been endorsed (Ref. 7), and even senior figures now openly support the concept (Ref. 8). To design a vehicle to achieve the cost targets necessary to start a commercial space tourism service is one of the objectives of the current Space Tourism Study Program of the Japanese Rocket Society (JRS).

After considering these arguments for considering the results to be unrealistically high, we should also note a number of arguments for correcting the figures upwards. These are first, the figures used for average salaries are those for Japanese manufacturing industry in 1990, which are significantly lower than national average incomes in 1993 at the time of the survey. Second, we have not included bonuses, which typically represent some 25 - 40% of annual income in Japan. Third, since we are considering the demand for a service to be available some years in the future, we should allow for economic growth in estimating salaries. If incomes grow at 3.5% per year, this would represent growth of 50% over 12 years, and 100% over 20 years. Fourth, it is a well-recognised feature of consumer expenditure in advanced countries, that once a certain income level is reached, spending on leisure activities increases proportionately faster than on other expenses, taking a larger share of income. Future spending on space travel would fall into this category. If we were to make allowance for all these factors, it is therefore arguable that we should increase the price at each demand level by as much as 100%.

As discussed above, it seems reasonable to assume that world demand for space tourism services might be 6 times greater than demand in Japan alone, although to be sure about this will require further surveys. Consequently, if we took the demand shown in Figures 1 and 2 as provisional estimates of world demand for space tourism, we would be effectively discounting our questionnaire results by some 90%. Thus it seems a reasonably conservative interpretation of our data to assume that world demand for orbital tourism services could reach a level of more than ¥1.2 trillion ($12 billion) per year at a service price of between ¥2.4 million ($24,000) and ¥1.2 million ($12,000). It therefore seems reasonable to conclude that the commercial revenue earned by space tourism services would be several times larger than the entire launch industry today, and has the potential to grow to many times its size. Consequently, in considering the design of a reusable launch vehicle from a commercial point of view, developing a vehicle for the tourist market seems to be an attractive target.

4. Pattern of development

The JRS Space Tourism Study Program assumes that the first phase of space tourism will comprise short trips to orbit lasting a few hours (Ref. 9). However, it seems likely that once space tourism begins, like other commercial activities the variety of space tourism services will grow progressively and, in particular, orbital accommodation will become available. At first no more than a simple "hostel" comprising a few accommodation units, these orbital vehicles will later become large and sophisticated "hotels", offering a range of entertainments that exploit the unique features of the orbital environment, as discussed in (Ref. 5). It is therefore interesting to consider the possible pattern of development of such services.

Although Figures 1 and 2 do not make any distinction between demand for different services, in our questionnaire participants were asked to state a preference between a day-trip to orbit, a trip lasting 2-3 days, a week-long stay in orbit, and a stay of 2 weeks or longer, without reference to price. The replies showed a strong preference for stays of a few days or longer, as described in (Ref. 1). From a commercial point of view the important questions are: "How much more would guests pay for a longer stay in orbit?"; "How much higher will the cost of providing such services be?"; and "How much greater would demand be for these services?"

Participants in the survey were not asked how much they would pay for different lengths of stay in orbit, but were asked to state their preference for a single visit length, independent of price. Consequently our data does not allow us to determine confidently the relative demand for trips of different lengths. Nevertheless, in the absence of more precise data, it seems reasonable to use the increasing popularity of different trip lengths at the same price as a proxy for the growth of demand that would occur as better services were offered.

Following this approach, Figure 3 shows the relative annual demand for the different stay lengths offered, on the same assumption as above, namely that annual demand is 4% of total demand. The revenue figure is not identical to that in Figures 1 and 2 above because we use a single average national income figure, which is not broken down according to age, but it is reasonably comparable.

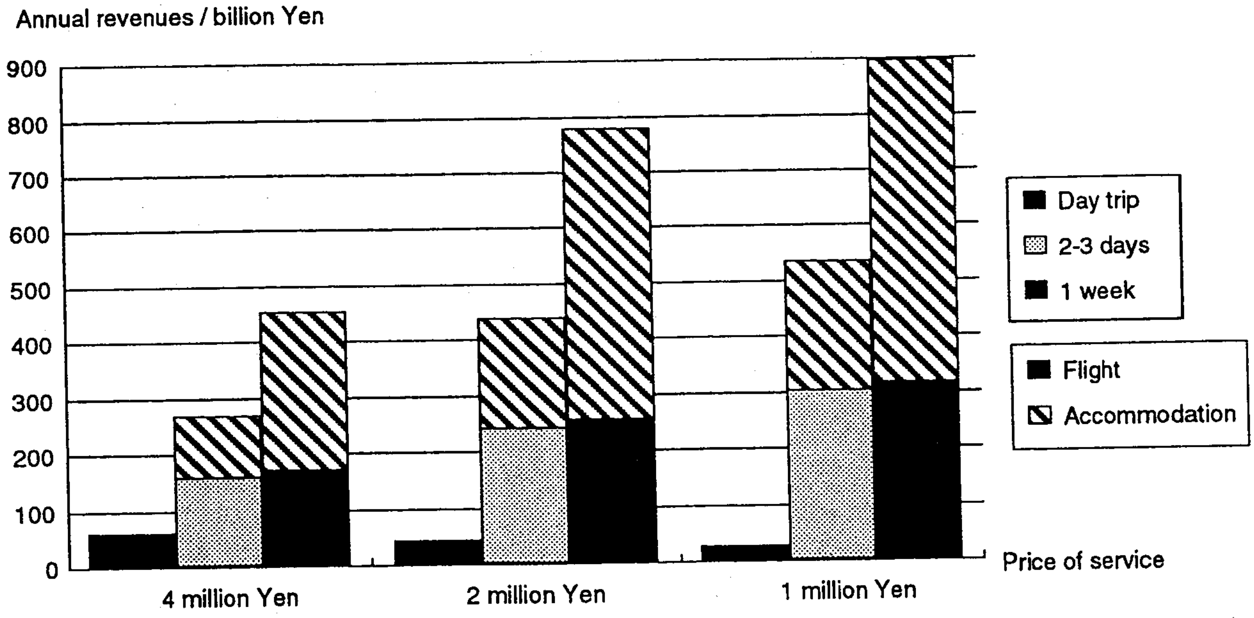

Figure 3. Growth of revenues from launch and accommodation.

As orbital accommodation services grew, the share of space tourism revenue accruing to launch vehicle operators would fall, as a larger proportion is paid for accommodation. Thus a significant proportion of the revenues shown in Figure 2 would accrue to operators of orbital accommodation rather than to launch companies. It is notable that the demand for stays of 2-3 days and 1 week show the same pattern of dependence on price, with a revenue peak at a price below ¥2 million. This is different from the demand for day-trips, which shows a different pattern, with demand being relatively inelastic and growing only relatively slowly as the price falls. However, this is of course affected by the increasing attractiveness of the alternative offerings at the same price. It is an important gap in the present data that, because the demand for longer stays in orbit is, not surprisingly, greater than the demand for day-trips at the same price, we can deduce little from our data about what the demand for day-trips would be at a time when this was the only service available - other than it would be greater than the figures in our results, which represent only those who would prefer a day-trip to a longer stay at the same price.

Thus, as space tourism services develop, as in other forms of tourism the overall price that passengers pay will comprise two separate components, that for flight to orbit and that for accommodation in orbit, and the price of each will fall progressively as demand increases. Stays in orbit will become available at a given price only once flight to orbit has fallen sufficiently below that price. Longer stays will become available later, when the price of shorter stays will be less than that of the longer stays.

If we make a simple assumption that the unit cost of launch services will fall according to a learning-curve of 90%, the cost of a flight to orbit will fall by about 30% as demand grows approximately 10 times from the day-trip phase to 2-3 days in orbit, and by about 37% as demand more than doubles again by the 1-week stay phase. Thus if the price of the service remained constant, as assumed in the questionnaire, the cost of accommodation would be successively 43% and 60% of the cost of flight to orbit. This is comparable to the rough estimate published in (Ref. 10) that the cost of a few days' stay in orbital accommodation will be approximately 50% of the cost of a flight to orbit. In the future we will analyse this in more detail, breaking down the data collected in our survey according to age and other factors. It will be interesting to compare the results with "bottom-up" economic analysis of orbital accommodation using inputs from the hotel and real estate industries (Ref. 11).

It is noteworthy that the growth in demand for orbital accommodation, measured by number of guest-days will be faster than the growth in launch demand, due to the growing length of stays. Consequently the service of providing accommodation in orbit has the potential to achieve greater reductions in cost (measured per guest-day) due to learning-curve benefits than have launch services. At a time when 1 million people visit orbit each year, orbital accommodation for 10,000 people or more will be required.

5. Commercially justifiable investment in passenger launch vehicle development

From the point of view of those considering investing in the development of a passenger launch vehicle, a question of central importance is "How high an investment cost can we expect to recover from profits from sales of vehicles?" In order to answer this we should make bottom-up estimates of vehicle operation and maintenance costs, propellant costs, staff costs and indirect costs. By comparing these with estimates of traffic rates at different prices, it would be possible to estimate justifiable vehicle price against passenger fare. By making further assumptions about vehicle production and sales, it would be possible to derive a figure for the maximum development cost that would be commercially recoverable. This is one of the intended outputs of the JRS passenger launch vehicle design study.

For the present paper we take a simpler approach. We assume a certain profit margin on the price that passengers pay. By doing this we can estimate the profit per year obtainable according to the vehicle utilisation. From the overall traffic we can estimate the number of vehicles needed, from which the maximum supportable investment can be calculated by making conventional financial assumptions. However, we must also take into account the fact that the flight price will fall progressively below the overall service price, which we do by assuming a 90% learning curve, as above. For Figure 4 we use the initial assumptions of the JRS passenger launch vehicle study, that each vehicle carries 50 passengers, and flies to orbit 300 times per year (Ref. 12). In addition we assume a 2% profit margin on the price of the passenger flight (which is less than the overall service price).

On this analysis, the most profitable flight price is about ¥1,200,000, corresponding to a service price of some ¥1,700,000. Development of a vehicle designed to fly passengers at such a price could be financed commercially at a development cost of up to some ¥150 billion ($1.5B), 25% more than a vehicle with passenger flight costs of twice this level. To provide the service would require 50 such vehicles, compared to only half this number of a vehicle with twice the passenger cost. The results of such a simple, preliminary analysis can only be considered tentative. However, the underlying concept of Figure 4 is fundamental to the future of the launch business.

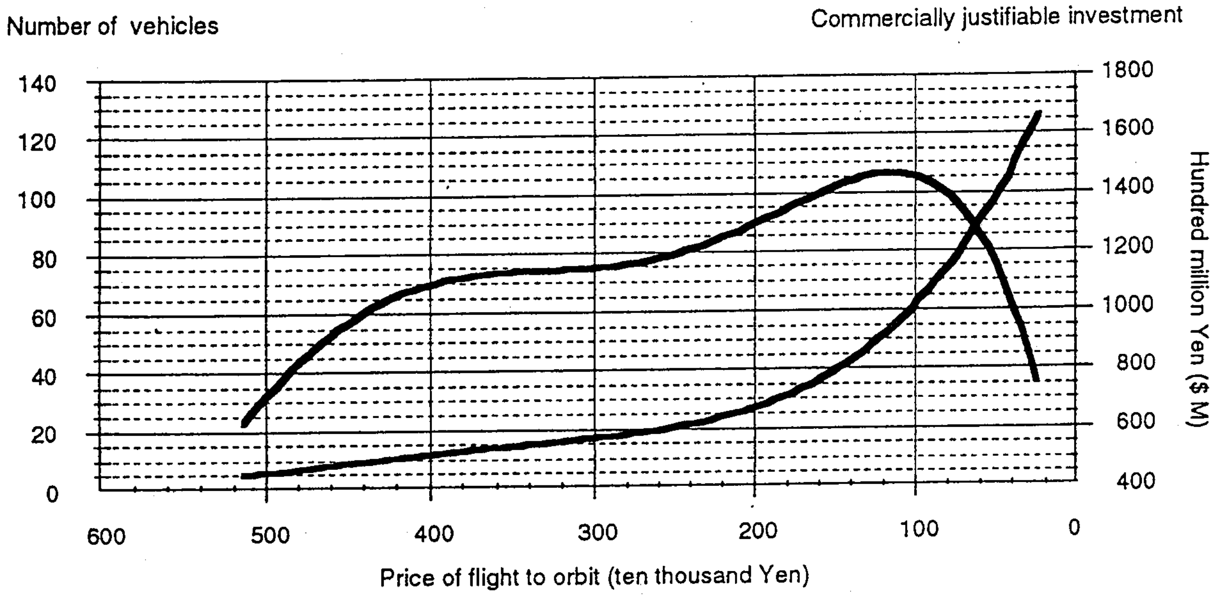

Figure 4. Commercially justifiable launch vehicle investment versus price of flight.

If further research on both the demand for space tourism and on the cost of supplying the services that people want supports our results, it is clear that carrying passengers to orbit and back has the potential to become a mainstay of the space launch business. No other payload which has so far been proposed in the space industry literature offers such a potential. The only other candidate for which launch demand could be of a similar or greater magnitude is the project to deliver solar-generated microwave power from space to Earth. This will become feasible only after a number of technologies have been developed beyond their present stage, in addition to the development of low-cost launch vehicles. By contrast, space tourism can start as soon as an appropriate vehicle is developed.

6. Further Results

Another interesting and potentially valuable subject not mentioned in the above discussion, which can also be analysed using the survey data, is market segmentation. As in terrestrial tourism, there seems to be a relatively inelastic demand for a high-priced service, and a separate, more price-elastic demand for low-price, mass-market "pack tours". From our results the possibility of a number of other more detailed categories of customer are apparent - graduation travel, young family holidays, "full moon" travel. These suggest directions for developing a range of distinctive space tourism offerings, which we will investigate further.

7. Conclusions

Although the interpretation of the data that we have collected is uncertain in a number of ways, at least some of the conclusions that we have drawn seem reasonably robust, and many are suggestive of the possibilities for developing a commercial space tourism business: Large numbers of people appear to be prepared to pay relatively high prices for visits to space. Once orbital accommodation is available, the demand for space tourism seems likely to grow to several times the demand for short flights in a launch vehicle. If the price of passenger flights can be reduced sufficiently to around ¥1.2

million ($12,000), the number of vehicles required could exceed 50, and the commercially justifiable investment in passenger launch vehicle development could be very substantial.

The simple examples described above are only a selection of the interesting and useful analyses that can be done with suitable market research data. However, they are sufficient to illustrate the potential of this approach, and to suggest areas for closer attention in follow-up surveys. We hope that more detailed and accurate analyses will be done using better market research data collected on this subject in several countries in the near future. In that case the prospects for developing a successful space tourism business will be greatly improved.

In considering such a prospect, the early history of aviation seems to offer many lessons. Basic decisions such as the number of passengers that a vehicle could carry were of fundamental importance to the economics of passenger carrying, and they depended on market estimates. Small differences in the design of different vehicles were sometimes responsible for major competitive advantages. The unending quest for better performance and lower costs to which the aircraft companies were driven by competition led to today's global aviation industry.

As in passenger aviation, energetic competition between a number of commercial companies building and operating reusable launch vehicles seems more likely to produce rapid reductions in cost than the continuation of launch operations by government monopoly organisations. And in order to provide sufficient scale for several companies to compete, a large market is needed. We suggest that space tourism has the potential to provide such a market.

The authors are interested in making their data available to interested parties, either for an appropriate fee, or in exchange for data or cooperation in research on space tourism of comparable value.

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SERVICES EXPECTED FOR THE FIRST PHASE OF SPACE TOURISM+

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Abstract

As part of the Japanese Rocket Society's current feasibility study on space tourism, this paper considers the services that should be offered during the first phase of such a business, namely providing short flights lasting just a few orbits. Companies offering such a service will need to plan several aspects carefully, including selecting orbital flight paths that offer interesting views of Earth, designing convenient seating and window arrangements, providing space for passengers to enjoy weightlessness, and making attractive vehicle interior designs. These considerations will be fed back to the JRS Sub-Committees studying vehicle design and general flight plans for space tourism.

1. Introduction

The Space Tourism Study Program of the Japanese Rocket Society is studying passenger transport to orbit as a possible near-future space activity that could create a demand for more rockets on a larger scale and at much lower cost than the present launch industry (Ref. 1). To provide a general guideline for inter-disciplinary studies by the Business Opportunity, Transportation and Medical Standards Sub-Committees, an industrial perspective shown by Table 1 was developed to provide a framework for studying the first phase of space tourism, in which passengers take short flights to low Earth orbit (Ref. 2).

Based on this first guideline, the Transportation and Medical Standard Sub-Committees have conducted feasibility studies in their specialized fields. This paper considers the requirements needed to satisfy the expectations of space tourists in the first phase of space tourism, based on the experience of those people who have been to space in the past.

For the purposes of this paper, the main attractions of space flight to be provided to passengers are considered to be Earth sight-seeing, and experiencing weightlessness during flight, as recommended in (Ref. 3). The main factors which will determine the quality of these entertainments are orbital conditions and vehicle accommodation. The influence of these in the first phase of space tourism is discussed in the following.

2. Earth sight-seeing

Recently preliminary market research has shown that, for the approximately 70% of the population who say they would like to visit space, the most popular activity in space is Earth sight-seeing (4). Thus this activity should be given priority in the first phase of space tourism. The sights on Earth that passengers can see from a space vehicle are determined primarily by the orbital conditions which are expressed mathematically by the six parameters of satellite orbits. From the point of view of service-providers and customers, orbital conditions can be interpreted as the take-off site, the direction of the

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flight and the altitude reached (which, together with the positions of the apogee and perigee, determine the track along the ground), the departure time, the flight duration and the landing site.

Table 1 Commercial Potential of Space Tourism

	Wide-bodied jet	Passenger launch vehicle
Production run	1000	50
Price (hundred million Yen *)	200	1000
Flights per year	720	300
Lifetime (years)	20	10
Amortization ** (ten thousand Yen)	220	4300
Fuel per flight (ten thousand Yen)	200	1600
Miscellaneous (ten thousand Yen)	200	2000
Total (ten thousand Yen)	620	7900
Passengers per flight	300	50
Cost / person (ten thousand Yen)	2.1	160
Passengers per year	200 million	750,000

* : 100 Yen is approximately 1 US $.
** : assuming 5% interest rate.

The factors that influence the value of a flight from the point of view of Earth sight-seeing can be divided into factors external to the vehicle and factors internal to the vehicle. That is, even if vehicles are designed to be capable of making orbital flights that go over appropriate regions or countries, passenger accommodation factors such as window and seat arrangements and the vehicle orientation during the flight will also be important to enable guests to enjoy Earth sight-seeing fully. The main factors that will be important are considered in turn below.

2.1 External factors

For the first phase of space tourism, in which passengers will remain within the launch vehicle, the choice of orbital parameters is in fact freer than it will be in the second phase, when launch vehicles will deliver passengers to an orbiting accommodation-vehicle or vehicles. In that case the range of possible take-off and landing times and sites will be tightly constrained in order to permit rendez-vous with minimum use of propellants. These constraints will not apply to flights in which passengers remain in the launch vehicle. In this case the factors to be considered include the following.

Take-off sites

Fully-reusable passenger-carrying space vehicles will be able to operate from much simpler sites than the launch sites of present-day expendable rockets. Ideally passenger flights should take off from many major airports, which are easily accessible and have air traffic control facilities. However at least initially just a few sites will probably be acceptable. Because most passengers will wish to see more than just the Earth's equatorial region, take-off sites near the equator will not have the advantage over high latitude sites that equatorial launch sites have today for launching satellites into geo-stationary orbit. Consequently many other places could be attractive take-off sites for passenger space flights, such as the 43 degree north latitude Tokachi District Space Flight Center project (5).

From commercial considerations, the number of take-off sites will be limited by the investment that will be needed in propellant-handling and other facilities. However, it could be a popular service if launch vehicles were used to make sub-orbital flights from a wider range of local sites to the main take-off "hub" sites for orbital flights. This could probably be done without requiring refuelling at the "spoke" sites, although it would also be possible to refuel the launch vehicle using a mobile propellant tanker.

Altitude

The view of Earth from low orbit varies according to the orbital altitude. In the absence of viewing aids the scenery of Earth seen from 200 km is fairly similar to that seen from higher altitudes such as 400 km (3), but the field of view grows wider with altitude. Thus a range of different orbits, including eccentric orbits in which the altitude varies considerably, perhaps reaching 1000 km or more at apogee, might be interesting for customers. At present it is not known what sorts of view would be most popular. Market research using simulations of views from different altitudes and with different viewing equipment could probably be useful to learn people's preferences.

For the short flights considered for this first phase of space tourism, very low orbits (or perigees) of some 100 kilometers altitude may also be interesting. These are unstable in the sense that aerodynamic drag from the upper atmosphere leads to re-entry within a few days, but for a flight of a few hours they could offer particularly good viewing, though over a narrower field of view.

Inclination

The inclination of the orbit will determine the maximum latitude of the Earth's surface that passengers will be able to see. Thus, although flights to equatorial orbits taking off from sites near the equator will have the lowest propellant costs to reach a given altitude, they will also provide the narrowest range of views of Earth - just a narrow strip round the equator. There are of course many interesting sites at higher latitudes; for example it seems likely that many passengers will wish to view their home-towns, and most people in advanced countries live at latitudes above 30 degrees. Consequently flights to relatively high-inclination orbits should be provided. In addition there will be demand for flights in polar orbits, which provide views of the Earth's north and south poles, as well as offering the possibility of seeing any point on Earth, depending on the orbital parameters.

Ground track

The views of Earth available during a flight will be determined in detail by the space vehicle's ground track. Companies providing passenger space travel services should select orbital flight plans that provide a particularly attractive range of views, and publish pamphlets showing different characteristic sights. Flights will probably be named after the main sight-seeing targets, such as "Tropical Jungles", "Polar Flight", "Pollution Watch", "Big City Lights" and so on. There is clearly wide scope for imaginative planning. Travel companies should also take care to avoid monotonous flights such as orbits that pass over oceans most of the time. The variety of ground tracks and areas visible could also be increased by using elliptical orbits in which the vehicle altitude varies widely during the flight.

Season

The views of Earth available will also vary according to the different seasons, which affect weather including storms, vegetation and so the colour of the landscape, natural phenomena such as snow cover and forest fires, and even human activities. Thus passengers may choose to fly at different times of the year according to their differing tastes. This possibility could become a significant attraction for repeat customers, who represent an important part of the demand in many businesses.

Since the weather, and particularly the degree of cloudiness which will greatly affect the view, varies according to the season, the demand for orbital flights will probably be seasonal. Thus companies may need to make considerable efforts to attract customers at off-peak times, such as by offering discounts, by improving the experience of weightlessness, or by emphasizing the viewing of space rather than Earth at times of poor weather at sites which are major attractions. It may also be necessary to re-schedule flights to see particular sights at short notice according to weather conditions, particularly at certain times of year. This would create some uncertainty for passengers, which would be inconvenient. But to the extent that such uncertainty is inevitable, such as for passengers wishing to view northern Europe in winter, it should be acceptable.

Short-term phenomena

Viewing of irregular phenomena such as snow falls, floods, volcanoes, forest fires and aurora could be planned only at short notice. For passengers interested in such sights, a service enabling reservations and bookings to be made at short notice would be necessary, as in the case of standby seats for passenger air travel today. For the time-frame under consideration, an inter-active service using electronic-mail bulletin boards might be attractive.

Take-off times

Orbiting the Earth at low altitude, passengers will spend about one third of each orbit in darkness. Those who have been to space have said that the view at these times is as interesting as during "day-time". The range of interesting "dark-side" sights includes such natural phenomena as lightning, aurora, bush-fires and volcanoes as well as human-made sights such as highways, city lights, fishing fleets and oil-field gas-flares (6, 7). Take-off times and orbital paths should therefore also be selected so as to include passing over sites that are interesting when viewed in the dark. Sunset and sunrise, which occur every orbit, are also said to be beautiful sights.

Landing Sites

While most passengers will probably wish to land at the site from which they took off, there will probably also be demand for flights landing at different sites. In this case the flight would have the bonus of providing "free" high-speed travel to the passenger's destination. The destination sites would usually be selected from the limited number of "hub" sites from which orbital flights were made. Such a service would overlap with the possibility of providing a world-wide sub-orbital passenger service. Though more expensive than passenger air travel today, this might become an important commercial service for reusable passenger launch vehicles, and would compete with supersonic air travel. Due to the ease of precise navigation in the era of GPS and other satellite navigation systems, sub-orbital charter flights might be arranged to and from many destinations.

2.2 Internal factors

During the first phase of space tourism passengers will remain within the launch vehicle throughout the flight which will last a few hours. Thus the accommodation arrangements within the vehicle will be very important in determining the conditions under which passengers can view the Earth.

Windows

The design of passenger windows, and particularly their size, position and depth relative to the vehicle's walls, will be very important for viewing outside the launch vehicle. Ideally passengers should each have their own window so that they can look outside continuously. Some passengers might be pleased to share a window another person, but probably only if it was sufficiently large and accessible for both to view at once. In this case some passengers might prefer to share with one or more friends, since this would enable them to discuss the view together. The astronauts who visited the US space station "Skylab" in the early 1970s suggested that windows should be surrounded by a wide area of free wall to enable people to view in any direction when in weightlessness. This would require a lot of space but would probably be popular. If free space was available above and below a window (even if not around 360 degrees), two people might share it in weightlessness viewing from opposite directions, rather than being side-by-side as on Earth. This might be an economical way to use windows.

If windows were not provided, but only electronic screens showing the view outside the spacecraft, it would be hard for a space tourism service to compete with the computer simulations of space flight that will become commercially available on Earth at much lower prices than actual space travel as "virtual reality" technology improves.

Passenger position

The quality of viewing outside will also depend on each passenger's position relative to the windows. It would be desirable if, once they reach orbit, passengers were free to float beside a window and look through it in any direction. This will require hand-grips and/or foot-grips at appropriate positions and angles beside windows to allow passengers to move and to anchor themselves easily in weightlessness.

During take-off and landing passengers will be in a more-or-less horizontal position, but they would like to be able to view outside the vehicle without moving their heads while the vehicle is accelerating, which is particularly disorienting. This might be achieved through the use of mirrors placed at the correct angle above their windows, which could be folded away during orbital flight.

Viewing equipment

For optimal sight-seeing, viewing aids such as binoculars would be helpful to allow passengers to see the Earth in more detail. Some passengers would like to take their own equipment, including cameras, which may have to be included in their mass allowance.

The recent innovation by some airlines of showing passengers the view from a camera in the aircraft's nose during take-off and landing would be particularly interesting for passengers in a launch vehicle. As in aircraft today, the view of take-off and landing, as well as other information, could be shown either on relatively large communal screens and/or on individual screens.

Vehicle orientation

The view that each passenger has will be strongly influenced by the vehicle orientation relative to the Earth and to passengers' windows and seating arrangements. For a circular seat layout, as suggested in (8) and analysed in (9), each passenger's view will be a little different from their neighbours. It will be necessary to take this into account when preparing the vehicle flight-plan in order to provide all passengers with attractive views. This could be achieved, for example, by pointing the vehicle's nose towards the Earth and maintaining a slow rate of rotation of the vehicle around its axis of symmetry, so that each passenger has experience of being at the "front" and at the "rear" of the vehicle. Maintaining a slow rotation like this might also be popular during take-off and re-entry, if it was feasible.

Lighting

In order to see well outside the vehicle, the lighting inside the viewing cabin should be relatively dim. As in aircraft, passengers should be able to adjust their personal lighting without irritating their neighbours. In addition, for viewing outside while in the shadow of the Earth it would be best if cabin lights were turned off to enable passengers' eyes to become fully dark-adapted.

Commentary

Many passengers would enjoy hearing a detailed commentary about the view of Earth that they can see. A range of different styles of commentary are possible, including different types of background music, which will be more or less interesting to different groups of passengers according to nationality, age, travel experience, and so on. Members of particular groups with common interests such as biology, mountaineering, astronomy, history, religion and so on could be specifically catered for in this way.

If passengers are seated in a circular layout their views of Earth will be different, which could require different versions of the commentary to be prepared. This could be handled relatively easily using individual screens and/or head-phones.

3. Experiencing weightlessness

For experiencing weightlessness the design of the space inside the vehicle will be of central importance. In particular, how large a volume is available, how many people will share it simultaneously, for how long each passenger may use the space, and what guidance they receive will determine how enjoyable the experience is. Factors which will have an important influence on the entertainment value include the following.

3.1 Volume

The larger the volume that could be available for passengers to experience weightlessness the better. Ideally, for an individual to practice moving freely in weightlessness a cubic volume at least some 2.5 meters across would seem desirable. However, if several people use the volume simultaneously, a larger volume would be necessary. In order for everyone to have the opportunity, it may be necessary for passengers to be allotted particular times for use of the space according to a schedule.

Unlike in aircraft, the space between each passenger's own couch and the cabin ceiling will also be available for floating in weightlessness. Since people will enter the cabin in Earth gravity, but will lie down for take-off and landing, the volume above the couch will be quite large - probably some 2 m by 2 m by 0.5 m. If the cabin ceiling was made higher than in aircraft this volume would be large enough for passengers to practice at least more restrained activities in their own space. This might be particularly popular with people who travel with family or friends, with whom they could share the combined space in turn or together. In this case, if a central space is also available, it should perhaps be used for more lively activities like gymnastics.

3.2 Time-table

Some passengers may wish to experience weightlessness, rather than viewing outside the vehicle, throughout the time between take-off and landing, and vice-versa. Some people may prefer to spend more time in the central space, in which case other people may be able to use those peoples' "personal" space. All this should be planned before each flight as far as possible in order to avoid disappointment for passengers not having the experiences they expect.

Passengers wishing to concentrate on activities in weightlessness may be numerous enough to justify operating a dedicated vehicle. This might have fewer windows than the standard vehicle, and have passenger accommodation arrangements that leave a wide-open interior space in orbit. For example, it might be possible to use a seating structure that folds away leaving an open two-storey space some 5 metres tall over the full width of the vehicle. This would enable passengers to enjoy weightlessness fully.

3.3 Guidance

Many passengers will enjoy the experience of weightlessness more if they could receive some guidance on how to move effectively, and about particularly entertaining "tricks". Some such instruction could take place before the flight, but it may also be desirable for one or more of the cabin crew, who should all be skillful in moving around in weightlessness, to provide guidance during the flight.

3.4 Play

As well as the experience of floating and moving around in weightlessness, playing with small objects is also said to be entertaining. This would be possible in passengers' own seating area. Playing with water is particularly entertaining (7, 10), but might require a special enclosure to prevent escaped water from irritating other people and causing danger for the vehicle. For this too, some guidance either before or during the flight would probably be helpful.

3.5 Equipment

In order to make the experience of weightlessness pleasant, well-designed hand-holds should be placed in convenient places to help people manoeuvre. In addition, to avoid possible injuries to each other, passengers should change their shoes for soft slippers or socks before the flight. Velcro tape might also be used on people's clothes and shoes to enable them to stabilise their position against the "floor" and "walls" of the cabin, which could be covered with an appropriate material.

4. Other entertainments

Although Earth sight-seeing and weightlessness are considered to be the main objectives of space tourism for the present study, a number of other activities will also be popular, and should be catered for as far as this is possible within the strong constraints on the cost and mass that will be commercially acceptable.

4.1 Viewing space

Those who have visited space say that the stars are much brighter and more colourful when seen from space. Astronomy is a popular hobby on Earth, and market research shows that astronomical observation would be popular (4), so many passengers will probably wish to view astronomical sights as well as the Earth. This will be easiest during the periods of "night-time" when the vehicle is passing through the Earth's shadow. As for Earth viewing it will be necessary to darken the cabin, and an expert commentary would probably also be popular, as well as viewing equipment.

4.2 Video & Photography

Many passengers will be keen to take videos and photographs as memories of their unique trip, both of the view out of the vehicle's windows, and of playing in weightlessness inside the vehicle. For passengers who wish to bring cameras with them, these will represent part of their mass allowance. Passengers will probably wish for advice confirming that their cameras will operate correctly in weightlessness. With the advent of electronic cameras and home fax machines, it might also be popular to provide telephone links for passengers to call or send pictures to friends on Earth.

It would probably also be a popular service for the travel company to make a video of each flight, including take-off, the view from the passenger cabin, passengers' activities during the flight, and return to Earth. This could be professionally edited and sold to passengers who wished for it. Since miniature video cameras are available, such videos might be taken automatically by a suite of preprogrammed video cameras mounted in the vehicle. Passengers might book in advance for extra video to be taken of them.

4.3 Eating & Drinking

During the early stages of space tourism flights will last only a few hours, and so meals will not really be necessary. However, as described in (3), passengers will certainly enjoy taking a meal in zero gravity, and so food and drink should be provided. As during vacations, many passengers may also like to drink some alcoholic drinks.

Although we teach children to have good table manners and "not to play with their food", passengers may wish to do this in weightlessness. Passengers will probably also wish to take photographs of eating, in order to remember these entertaining aspects of weightlessness, as the American astronaut Joe Allen was photographed playing with his orange juice.

4.4 Recognition

Another aspect that will be significant for many passengers is providing formal recognition of their visit to space, as described in (3). For example it is traditional in the USA to give an "astronaut badge" to anyone who reaches an altitude of 50 miles or more, in recognition that they have visited space. There are also a number of clubs around the world of which passengers could become members after they have visited space. It is likely that other such clubs will also be formed as the number of people who visit space grows.

At present the number of people who have visited space, or reached orbit, is known precisely. Thus, for some years to come it will be possible to provide passengers with recognition of being, for example, the 2049th member of the human race to visit space. Such historical significance might be attractive to many people. A business such as the Guiness Book of Records might collaborate in such an activity.

4.5 Omiyage

Many passengers will wish to buy "omiyage" for friends as mementoes of their space flight. Although carrying these on board the vehicle will be expensive, small light-weight items such as cards, cakes, handkerchiefs etc, may be popular even at prices which reflect their transport cost. Videos of the trip, as mentioned above, will also be popular. As at airports, many other goods would probably be popular even if available only on Earth.

5. Other factors

There are a number of factors in addition to the above which will have a significant effect on passengers' enjoyment of space flight, and so on the commercial demand for orbital tourism services.

5.1 Safety

As emphasized by Professor Mitarai (11), trust in the safety of the passenger vehicle is a fundamental requirement to generate substantial commercial demand. Like aircraft, in order to obtain certification and insurance the vehicles will have to achieve a high level of reliability through flying repeatedly. In addition, safety procedures and equipment such as emergency oxygen-masks similar to those provided in aircraft will be necessary.

Public perception of safety is influenced by other factors than safety statistics alone. For example, in the early days of aviation in the USA the first trans-Atlantic flight led to the "Lindberg boom" in demand for passenger flight. The "Ford Reliability Tours" started by Henry Ford to improve both the reliability of aircraft and public perceptions of aircraft safety were also extremely valuable (12). Similar activities may well be valuable in increasing the public's confidence in space travel.

In addition to vehicle safety, other objective factors such as the establishment of effective aerospace traffic control, space debris reduction, and avoidance of such relatively dangerous regions as the South Atlantic Anomaly will be important.

5.2 Bodily comfort

It will be very important for passengers to feel well throughout their space flight. For this, problems such as "space sickness" and congestion in the head need to be resolved. Although about 50% of those who have visited space have suffered from temporary nausea, a number of anti-emetic drugs have recently been found to be highly effective in preventing this (13). As a result NASA has reportedly stopped further research on this subject. For holiday-making passengers possible side-effects of medication such as slight drowsiness, equivalent to the effect of drinking a little alcohol, seem sure to be acceptable. Since, as on board a ship, if one passenger vomits others feel less comfortable, it may be appropriate to establish a standard treatment for all orbital passengers such as a standard dose of Promethazine sometime before take-off.

The feeling of congestion in the head caused by redistribution of body fluids in weightlessness can be irritating for some people, and could be rather unpleasant for people suffering from a cold. It may therefore be necessary for passengers who catch a cold shortly before their flight to take some appropriate medication, or to re-schedule their flight. Some pre-flight preparation, such as physical training and/or medication, either at home or during a pre-flight residential period leading to partial reduction of body fluid before flying may help to make people comfortable in weightlessness.

A number of minor bodily discomforts on Earth can be more irritating in weightlessness. For example, many people experience occasional discomfort from having one nostril blocked, and unblock their nostril by tilting their head to one side. This remedy depends on gravity, and so is not available in weightlessness. Consequently it may be desirable to have medication such as nasal sprays available to overcome such discomfort. Stomach gases can also be uncomfortable in weightlessness, and so counter-acting medication would be useful.

5.3 First aid

As on aircraft it will not be necessary to treat serious injuries. However, there are a number of minor injuries that people may suffer, in part because of being in an unfamiliar weightless environment, which it will be useful for cabin staff to be able to treat. These include nose-bleeds, minor cuts and bruises, getting something in the eye, choking, and spraining or dislocating a finger. People wearing contact-lenses or spectacles who experience difficulties may also need help.

5.4 Toilet facilities

Providing full toilet facilities like those on aircraft would be expensive and heavy, but at least some minimal facilities will be necessary. As described in (2), using a wash-basin and/or toilet in weightlessness is different from using one on Earth and may well be of interest to passengers.

5.5 Preparation

For flights lasting a few hours, as proposed for the first phase of space tourism, some preparation may be enjoyable, though passengers will have different preferences. Travel companies should produce a detailed booklet providing advice for customers, giving guidance on such matters as health and moving in weightlessness. Many people may wish for reassurance that space flight is not medically dangerous, and that they do not need to be unusually healthy in order to visit space - a common misunderstanding. There may also be considerable demand for a residential training period of a few days providing an entertaining preparation for space flight. There is likely also to be a lively market for books about space flight written by well-known writers and "tarento" who have travelled to orbit themselves.

5.6 Music

As in commercial aircraft flights, many passengers will probably enjoy listening to music in orbit. This may be catered for as in aircraft both collectively through cabin loudspeakers, and individually through headphones.

5.7 Interior design

Although less critical than the space vehicle's engineering design, the interior design of the passenger cabin will be very important for the public. Like many other aspects mentioned above, this also provides the vehicle production company with a good opportunity for publicity, due to the great interest that the media are sure to take in every aspect of space tourism, and particularly those aspects that can be shown in photographs and on video.

The people who visited the space station "Skylab" differed considerably in their reaction to living in weightlessness. Some enjoyed the strangeness of complex perspectives, and some found them confusing, and wanted a strong "local vertical" as in a one-gravity environment. It should be remembered, however, that the people who lived in "Skylab" were always very busy with work, and weightlessness was irritating to them because it slowed their work. For holiday-makers weightlessness will not be irritating in this way, but will mainly be entertaining, particularly since "space sickness" is no longer a problem. Thus there is scope for interesting experimentation in the interior design of a passenger vehicle, intended to give an exciting "feel" to the new world of weightlessness.

As in any closed environment, an air-conditioning system will be needed to keep the air fresh and pleasant-smelling. In addition since, since dust will not fall to the floor as in aircraft, it will be desirable to keep the amount of dust in the air very low in this way, in order not to irritate people's eyes. A functional idea learned from the US Space Station "Skylab" was that it is useful to have a noticeable air current moving through the vehicle, since things that get lost usually arrive at the filters over the air-intakes of the air-conditioning system (7). In a passenger vehicle some people are sure to lose things, so such a system could be useful. From a more basic point of view, it will be necessary to design the interior to have no sharp projections against which passengers floating around the vehicle in weightlessness could hurt themselves.

Electronics designers must also consider such details as providing screens showing the vehicle's current altitude, velocity, latitude and longitude in order to give passengers a feeling of the unique quality of space flight. This might be integrated with the other information functions mentioned above in a "passenger data system". In combination with other electronic systems such as a video network and telephone links to Earth, the passenger service electronic system would be an interesting project for electronics makers, separately from the vehicle avionics.

5.8 Clothing

People who have been to space have also learned lessons about suitable clothing. These concern such matters as allowing for the small changes in body shape that occur in weightlessness, and having pockets that retain their contents effectively in weightlessness. Thus it will be useful for space tourism companies to offer passengers advice on this matter, and also to offer suitable clothing for sale. Clothing of course also has importance for people for non-functional reasons. If space tourism becomes a popular pastime, it seems likely that innovative clothes manufacturers will produce a range of fashionable clothes designed for use in the unique environment of weightlessness.

5.9 Charter flights

As in the case of aircraft, there will probably be a significant demand for charter flights, that is block-bookings of a launch vehicle by a group of people who wish to travel together. This is particularly likely if launch vehicles carry as few as 50 passengers, as assumed in the JRS study (14), in which case a range of different social groups might use such a service, such as astronomy clubs and travel clubs. It also seems likely that some religious groups would arrange for members to travel to space together to view the Earth and the Universe. Such markets could no doubt be stimulated by appropriate creative marketing.

6. Conclusions

Even for the first phase of space tourism, in which passengers will make orbital trips of a few hours, there are clearly many different aspects of the passengers' experience that must be considered and planned in detail in order to provide a satisfying service - which is the key to commercial success.

Simulation of space flight using a detailed mock-up of a passenger cabin could be useful for determining potential passengers' preferences concerning such aspects as seating and window layout, orbital paths, view of the Earth and vehicle orientiation. Experiments in an aircraft performing parabolic flights could be useful for studying the accommodations needed for inexperienced passengers to enjoy weightlessness.

In addition to the functional aspects of passenger launch vehicle design, the interior design of such vehicles also provides exciting opportunities for industrial designers. Holding a competition for such designs might be a good way of stimulating new ideas while obtaining useful publicity.

The results of ongoing studies on the above subjects will be fed back to the Japanese Rocket Society Sub-Committees studying vehicle design and general flight plans, as well as to those studying the medical and business aspects of space tourism.

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VEHICLE DESIGN FOR SPACE TOURISM+

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Abstract

A fully reusable SSTO (Single Stage to Orbit) rocket vehicle of vertical takeoff and landing type has been conceptually designed as a standard transportation model for space tourism by the transportation research committee of JRS (Japanese Rocket Society). The design criteria of the vehicle have been assumed based on the services required for space tourism. The standard vehicle is operational for a maximum 24 hour space tour of 50 passengers in low earth orbit. Within the reach of our near future rocket technology, the design results in 22m body length and weight of 550 Mg using MMC, CF/Epy and Ti/Mw advanced materials. The 12 engines, which can be throttled and gimbaled during the whole mission time, perform vertical launch and tail-first reentry to final landing within tolerable acceleration acting on passengers. Two floor decks with sightseeing windows and a microgravity amusement space are provided as an attractive passenger service.

1. Introduction

In 1993, the Japanese Rocket Society (JRS) adopted space tourism as a research project for future space activities of mankind (ref. 1). The purpose of the research is to give a new and strong motivation for commercialization of space transportation by studying space tourism from various viewpoints of different disciplines, such as space medicine, business or passenger service. Such a study has never been made in the history of Japanese rocket development.

As discussed (ref. 2), aerospace companies are expected to make considerable efforts to produce low-cost space transportation vehicles on the grounds of seeking a new space transportation market, namely space tours. Since most people have no doubt about the fascination of flight to orbit, only the 'how' and 'when' of its realization are open to question. Spreading the market to establish regular 'Spacelines' from ground to orbit will result in a miraculous cost reduction in space vehicle production and flight operations.

The transportation research committee of JRS was established to study real space vehicles which could be used for tourism. The committee members consisted mainly of the corporate members interested in this subject. As a result of regular workshops of the committee, this paper summarizes the first year status report of the standard design criteria for the vehicle and its operation. The propulsion system design (ref. 3) and related study on liquid hydrogen technology (ref. 4) are included in this issue.

Besides a guideline proposed by the JRS Committee for Academic Activities, the first phase space tourism study (ref. 5) was used to clarify the features of space travel concerning tour courses and cabin services similar to those provided by commercial airlines. In order to define a vehicle concept for space tourism, a vertical takeoff and landing fully reusable SSTO (Single Stage to Orbit) rocket vehicle was chosen without a detail tradeoff with aerospace planes. This type of vehicle has been

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+ Revision of ISTS 94-g-22p presented at the 19th International Symposium on Space Technology and Science (ISTS Yokohama), May 15-24, 1994.

studied by several authors (refs. 6,7,8 & 9). For the size of the vehicle, this study assumed that the lift-off mass should be equal to the take-off mass of a typical wide-body airplane.

2. Space Tourism Model as Vehicle Design Guideline

According to a comment on the pleasure of spaceflight by the first Japanese astronaut, Akiyama, the basic commercial values of a space tour are the experience of weightlessness and Earth sightseeing (ref. 10), and further considerations on space tourism services have been made for the JRS Space Tourism study (ref. 1). Based on these comments and considerations, Table 1 summarizes the types of services which space tourists can expect in an early space tour. The space vehicle is expected to provide passengers with these unique experiences which differ completely from the current virtual reality amusement.

Table 1 Space Tour Service Model

Type of service	Services for 2- Orbit Flight	Additional Services for One-day Flight
Sightseeing	Daytime Departure -Pacific Ocean -South America Night Departure -Africa -Asia	Observation of most of the Earth (Day and night scenes depend on departure time.)
Amusement	Experience of Weightlessness, Astronautical Observation and Telecommunication	Longer Experiences
Cabin Service	Soft drink	Breakfast/Lunch/Dinner
Others	Recognition and Souvenirs	

In Table 1, the first standard flights are assumed to be two of orbit flights, and the second ones would last for twenty-four hours. As can be seen by the ground track of Figure 1, a vehicle leaving Japan flies first over the Pacific Ocean to Argentina. Then it passes the center of Africa to cross India and China. The passengers can enjoy spectacular scenery of their home town from the altitude of 200km. On the second orbit the vehicle flies over Hawaii. The vehicle then deorbits over Africa to pass the reentry interface at an altitude of 100km in the middle of China.

Such a scenario implies technical requirements of vehicles to be used for space tourism in the near future. The following are typical design factors to be considered.

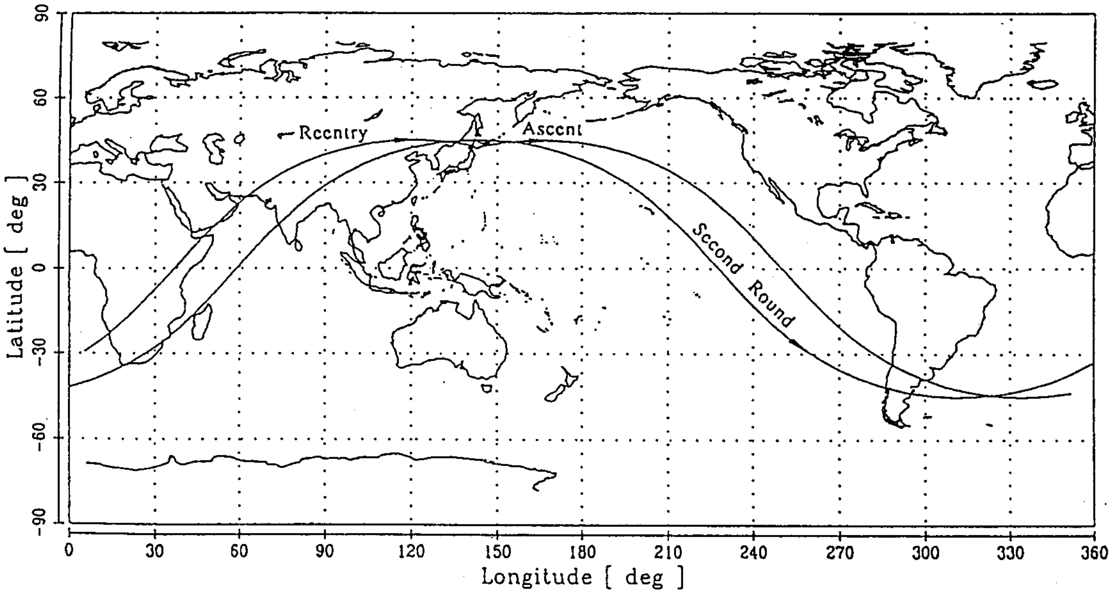


Figure 1. Ground track of two orbit space tour.

Figure 1. Ground track of two orbit space tour.

Altitude

According to Akiyama's comments, flying at higher altitude does not necessarily provide better sightseeing, based on his flight in the space station Mir. Thus, the altitude of 200km is assumed to be our standard orbit for sightseeing. No orbit transfer capability will be provided.

Orbit Inclination

Usually, a space vehicle can carry a heavier payload when it takes off eastward from lower latitude. In this respect, the equatorial zone is the best site for spaceports. However, higher inclination orbits have an advantage in providing passengers with a wider range of more attractive views of Earth from the equator to the high latitudes, at the sacrifice of payload injection capability depending on spaceport locations. A space vehicle for space tourism should have enough launch capability to satisfy this demand and to match the population distribution of prospective tourists.

Tour Time

The maximum flight time of 24 hours can be preliminarily determined by the tour requirement to provide views of the whole Earth in daytime. This maximum time is also set by trajectory restrictions for return to takeoff sites located at relatively high latitude.

On the other hand, the minimum flight time that the transportation research committee has planned is two orbits. This minimum time came from the necessity of preparing for deorbit. Since one third of each orbit time is in darkness, the departure time is significant for selection of sightseeing course.

Cabin Arrangement

Two important but difficult requirements that the vehicle designer should take into consideration are windows for sightseeing and a room for experiencing weightlessness. In order to distinguish real space sightseeing from computer play like virtual reality, the vehicle provides as many windows as possible. The medical research group suggested that some passengers may have to observe the earth sitting in their own seats for physical reason such as space sickness (ref. 11). A microgravity amusement space will be necessary for passengers to enjoy floating in weightlessness safely.

The ideas of facilities currently used by airlines such as galley, toilet, miscellaneous utilities, television screen for monitoring scenery and sightseeing commentary system will also be helpful in designing the cabin arrangement.

Medical Restrictions

Passengers will experience the greatest acceleration during ascent to orbit and atmospheric reentry. Although it was requested that the acceleration shouldn't exceed 4 G from head to foot and 2 G in the reverse way, a stricter acceleration level of 3G from head to foot and 0G in the reverse direction was used for this design study (ref. 12).

Another medical problem is space sickness. Although there is no standard to design the vehicle against space sickness, provisions for future medical treatments and first aid will also be used in designing the cabin.

3. Vehicle Concept Definition

3.1 Reentry Style

The configurations of SSTO rockets are classified by atmospheric reentry style into two types; nose-first reentry configurations and tail-first reentry configurations. Vehicles that perform the nose-first reentry have a relatively slender body like the Delta Clipper (ref. 9), which reduces the aerodynamic drag to achieve better orbit injection capability and attains relatively large cross range capability during the reentry phase. However, nose-first entry vehicles require a maneuver to rotate 180 degrees in the atmosphere before they land vertically. This maneuver brings difficult problems to vehicle design in terms of acceleration control, that are critical for passenger accommodation and for surface control of liquids in propellant tanks (ref. 13).

On the other hand, tail-first reentry vehicles like the BETA (ref. 7) and the Phoenix (ref. 8) can avoid these problems, although the cross range capability for this type is considered to be smaller than nose-first reentry vehicles. From this view point, a tail-first type of vehicle has been adopted for

3.2 Performance Requirement

The orbital condition and total velocity requirement are summarized in Table 2. The orbital altitude is 200km with inclination of 45 degrees. A velocity increment of 300m/s is assumed for the vertical landing maneuver and 290m/s is added to the total velocity as the performance margin. The resultant total velocity of 9.93km/s is relatively large compared with that for the BETA or the Phoenix.

Table 2 The Total Velocity Required for One Flight of Reference Vehicle

Mission Phase	Velocity Increment	(km/s)
Ascent	Orbital Velocity	7.701
	Gravity Loss	0.900
	Drag Loss	0.600
	Maneuver Loss	0.070
Descent	Deorbit Impulsive Velocity	0.070
	Landing Maneuver	0.300
Reserved for design		0.290
Total Velocity		9.93

3.3 Configuration Design

The design of vehicles for space tourism depends heavily on the users' request of sightseeing and weightlessness experience. Thus the cabin arrangement has much influence on the configuration of the vehicle. The design results in a body length of 22m with a bottom diameter of 18m as shown in Figure 2.

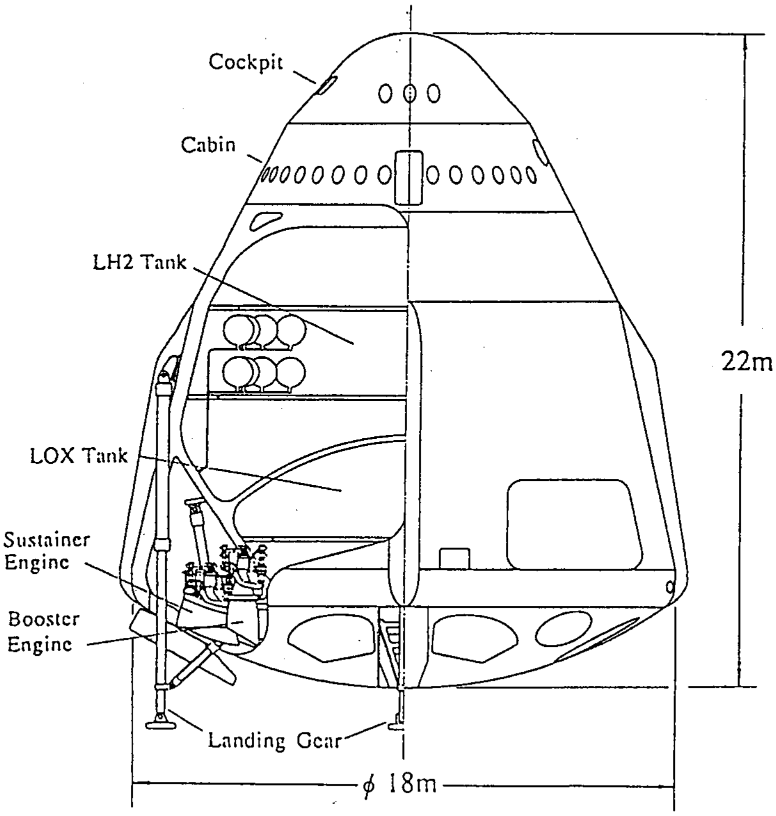


Figure 2. General view of the vehicle.

A two floor cabin with many sightseeing windows and a microgravity amusement space makes the top of the vehicle in upright position. The propellant tank is a semi-integral structure using advanced material to reduce weight, which has a common bulkhead between LH_2 and LOX propellant tanks.

Twelve engines, four booster engines and eight sustainer engines, with conventional bell nozzles are mounted in a circular position around the lower tank structure. Nozzle expansion ratios are 15 for booster engines and 40 and 80 (two positions) for sustainer engines, respectively.

The vehicle has four linkage type landing gears, which can be retracted in the body. The energy absorption concept is a conventional oleo pneumatic system. To prevent toppling of the vehicle in case of one landing gear failure, the length of the opposite oleo stroke is shortened.

3.4 Cabin Arrangement

Figure 3 shows the comparison of two cabin arrangements that were considered. One lines up passenger seats parallel like current airlines (above) and the other, recommended as better by astronaut Akiyama (ref. 14) adopts the seats arranged in circles to provide better views through the windows (bottom).

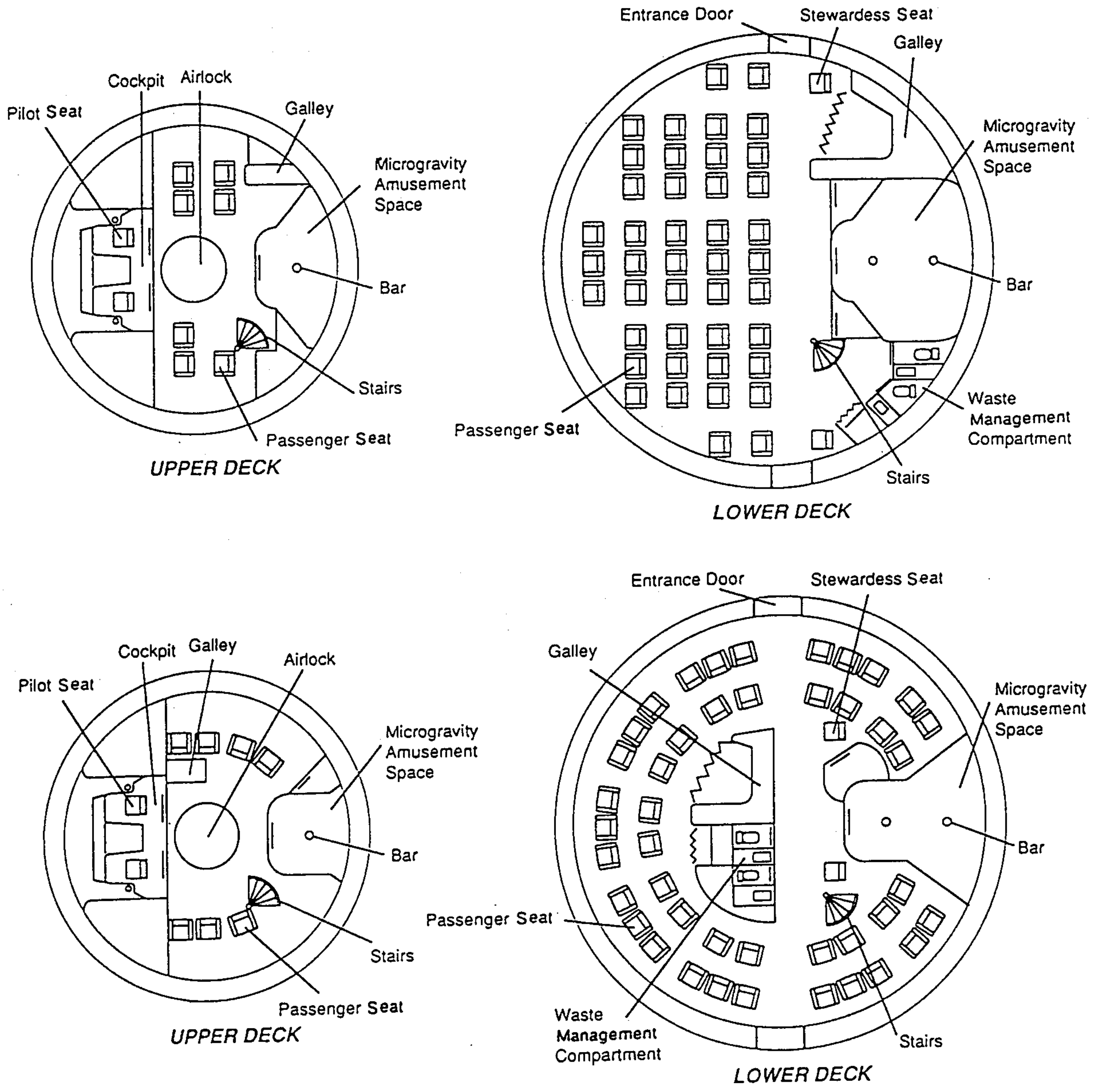


Figure 3. Cabin plans: in-line seat arrangement (top) and circular seat arrangement (bottom).

3.5 Mass Characteristics

The mass characteristics of the present vehicle estimated in the first phase design work is shown in Table 3. It should be noted that the total lift-off mass exceeds the target mass of a widebody aircraft.

Table 3 Mass Characteristics of Standard Passenger Vehicle (unit : kg)

Subsystem ⁄ · Items		Subtotal	
1. Structure		15,959	
· Engine Skirt	3,860		
· Engine Thrust Structure	2,063		
· Main Cabin Structure	2,009		
· Cockpit/Cabin Structure	2,436		
· Thermal Protection System Heat Shield (including Sustainer E/G Cover)	3,944		
· Landing Gear System	1,375		
· Airlock System	272		
2. Propulsion System		29,517	
· Sustainer engine	9,456		
· Booster Engine	4,184		
· LH2-Tank	8,888		
· LOX-Tank	4,089		
· Auxiliary Tanks (LH2 and LOX)	450		
· Pressurization System (AHe and CHe)	1,950		
· Reaction Control System	400		
· Feed System	100		
· Residual Propellant (excluded in subtotal)	2,475		
3. Actuator System		820	
· Auxiliary Power Unit	220		
· Miscellaneous Actuators and Pumps	600		
4. Environmental Control System		1,100	
5. Power Supply System		580	
6. Navigation, Guidance and Control System		305	
7. Communication and Data Acquisition System		431	
8. Miscellaneous Equipment		1,542	
· Passenger Seats	1,127		
· Crew Seats	62		
· Galley	122		
· Toilets	130		
· Miscellaneous	100		
Empty Vehicle Mass			50,254
9. Passengers and Crew Weight		4,320	
· Fifty Passengers	3,750		
· Crew (four persons)	300		
· Luggage	270		
10. Propellants (including Residual Propellant)		494,918	
· Fuel (LH2)	70,703		
· Oxidizer (LOX)	424,215		
Total Lift-off Mass (including design margin of 597 kg)			550,089

4. Subsystem Design

4.1 Aerodynamic Design

Aerodynamic design of this vehicle is mainly concerned with aerodynamic stability and cross range control during the atmospheric reentry phase. The present vehicle employs four body flaps at the engine skirt section, the two windward flaps of which act as angle-of-attack trim control, and the two leeward flaps are utilized for lateral stability. A calculation model shown on the right hand side of Figure 4 was used for the aerodynamic analysis of the vehicle.

As a result shown by Figure 4, the vehicle can attain lift-to-drag ratios of 0.3 and 0.4 at angle-of-attacks of 20 and 35 degrees respectively in hypersonic flight. Since the lifting body characteristics are about one third of the current performance of Space Shuttle and lower than the predicted Delta Clipper capability (ref. 15), it may not fully satisfy the cross range requirement to return from high inclination orbits on a contingency basis.

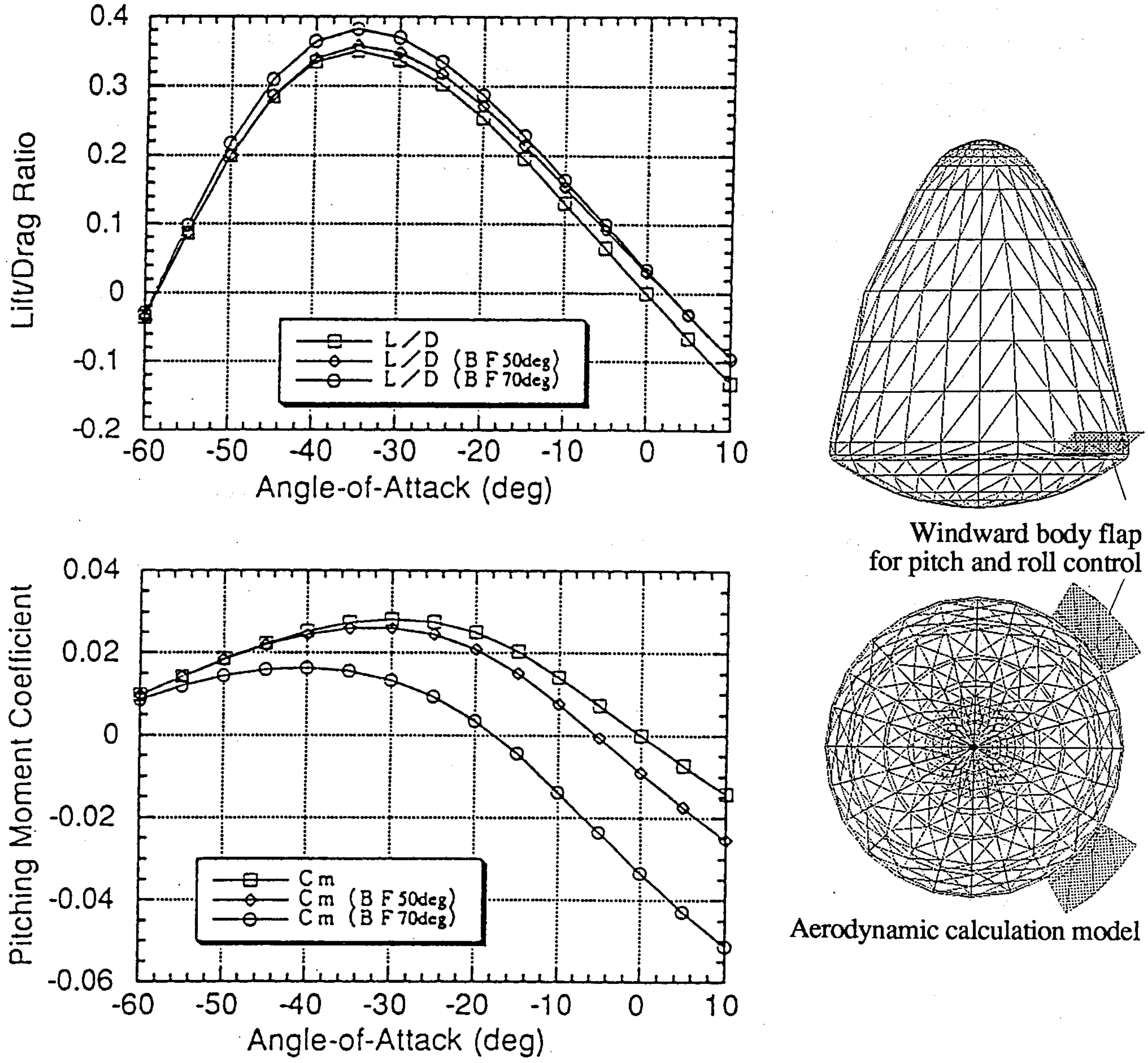


Figure 4. Lift-to-drag and trim characteristics calculated with the model shown.

4.2 Propulsion Design

At the beginning of the vehicle design for this study, the requirements for the propulsion system have been analyzed. Consequently, a standard type of cryogenic propulsion system using liquid hydrogen and liquid oxygen as propellants rather than slush hydrogen has been selected due to their well-known characteristic. For a similar reason as well as for flexibility in engine-out contingencies, the tradeoff study of engine nozzle types resulted in selection of bell nozzles rather than a plug nozzle. The number of booster and sustainer engines has been determined to fulfill the requirement of total thrust-to-weight ratio at liftoff between 1.3 to 1.5, and intact abort criteria to keep the thrust-to-weight ratio more than one in case of two engine failures, based on practical data using 80% thrust level of LE-7 engine enhancing reliability and life cycle. Although the orbit injection capability would be increased with more sustainer engines, a combination of four booster engines and eight sustainer engines has been adopted due to the limitation of the vehicle base area shown in Figure 5. For the terminal powered flight during landing, two booster engines will be activated while the other two are put in idle mode preparing for engine failure.

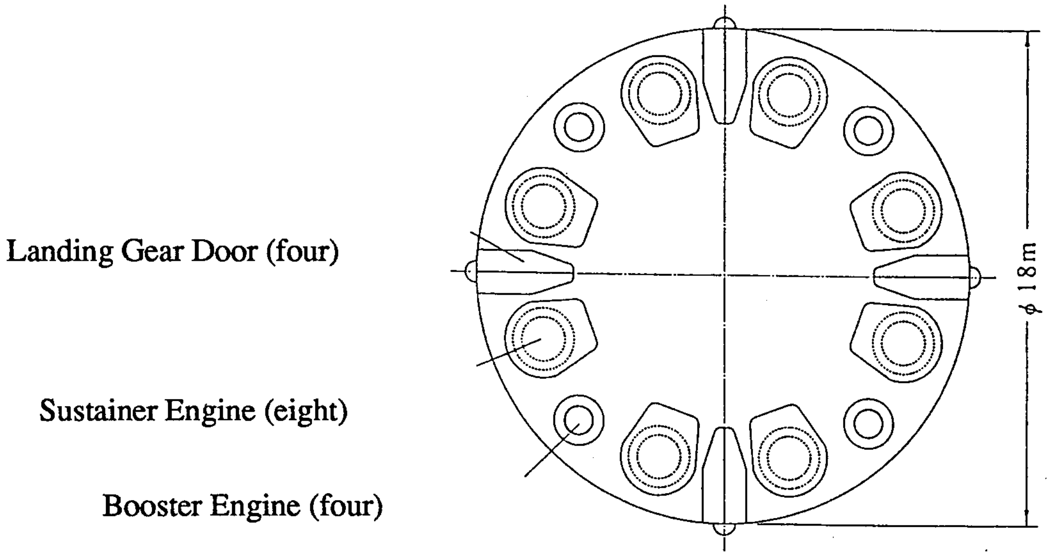


Figure 5. Bottom view of the vehicle to show engine and landing gear arrangement.

Angular acceleration required for the reaction control system is 1 deg/s^2, which results in about 7000N class thruster using GOX/GH2 propellant. The total impulse requirement of 4.2mNs was estimated to satisfy the rotation duty needed for Earth sightseeing.

4.3 Structural Design

The most important requirement of structural design is to minimize the mass of propellant tanks containing low density liquid hydrogen propellant, and of the sophisticated reusable thermal protection, which are critical for the performance of SSTO vehicles.

This design study is based on another study (ref. 16), which compared various candidate materials and structural systems originally developed for future aerospace planes, in terms of a performance parameter of "unit mass" defined by structure mass per structure surface area. The result is summarized in Figures 6 and 7 for the primary structure and integral tank structure, respectively. The unit mass targets specified in both Figures are based on design requirements of various vehicles. Figure 6 shows that present technology can realize the targets for the primary structure. On the other hand, present technology cannot satisfy the requirement for the integral tank structure as shown in Figure 7. It will be necessary to design the tank geometry to minimize the surface area of the constant volume tank.

Considering not only the technical but also the economic aspects of these structures, we have designed structural systems for the present vehicle with light weight combinations of conventional TPS (Thermal Protection System) and advanced structural system to meet the thermal conditions of various parts of the vehicle as shown in Figure 8.

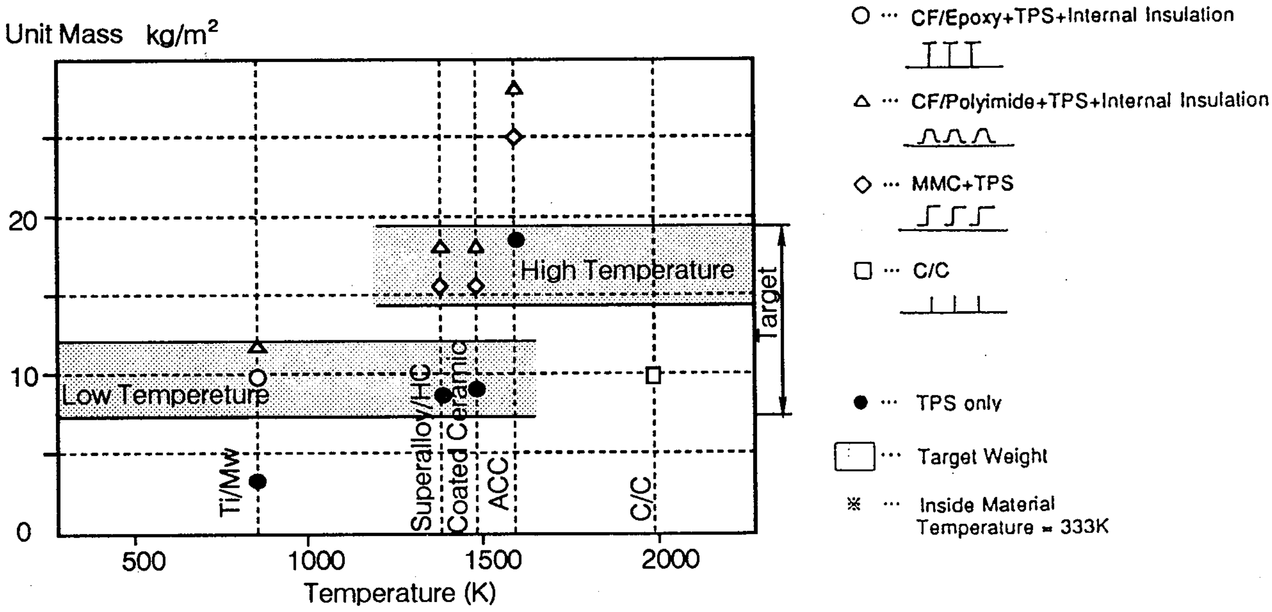


Figure 6. Design targets and forecasts of advanced materials for primary structure (ref. 16).

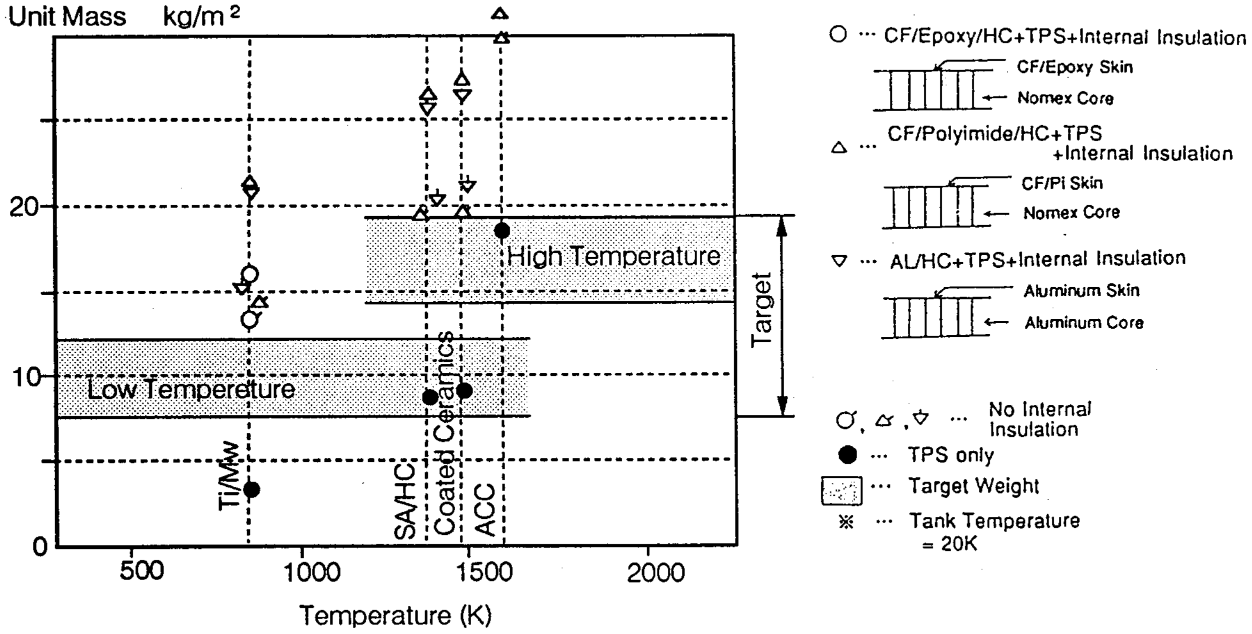


Figure 7. Design targets and forecasts of advanced materials for cryogenic tank structure (ref. 16).

4.4 Navigation, Guidance and Control System

Avionics for the navigation, guidance and control system for the present SSTO vehicle has no critical design issue. Attention will be paid to the onboard software design for both the ascent and reentry phase to calculate not only the optimal trajectory guidance and control, but also to manage various failure modes safely (ref. 17).

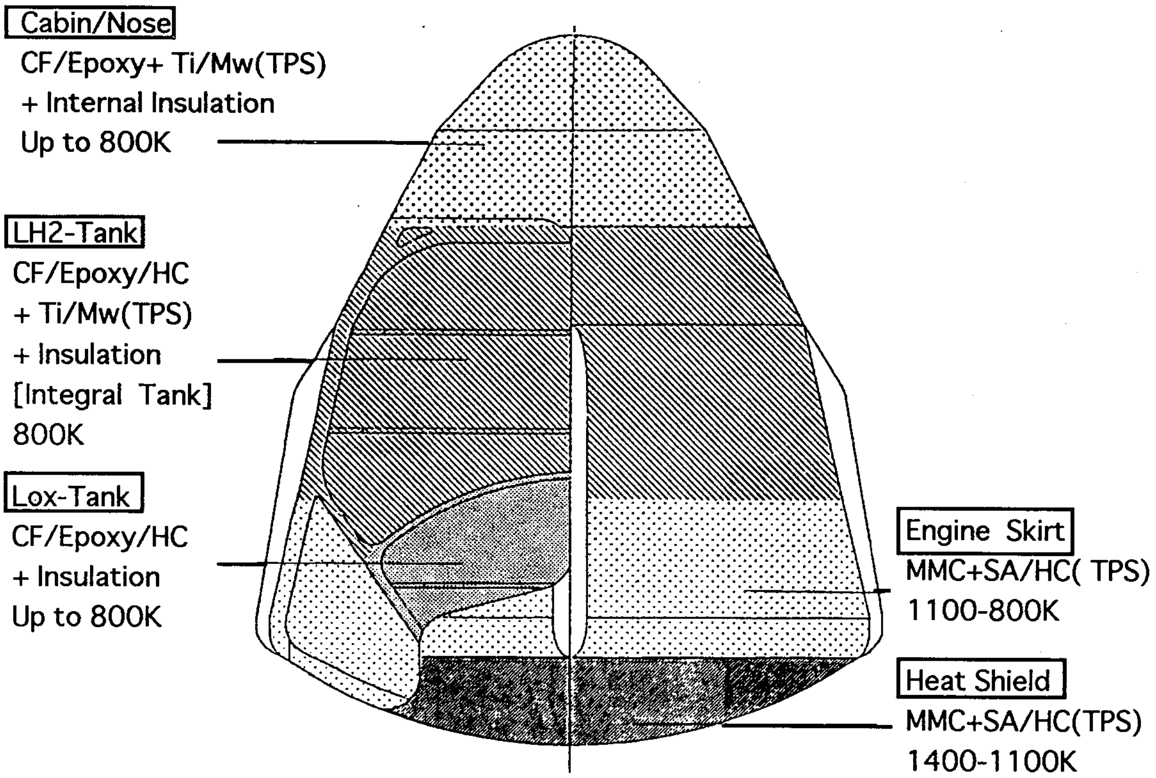
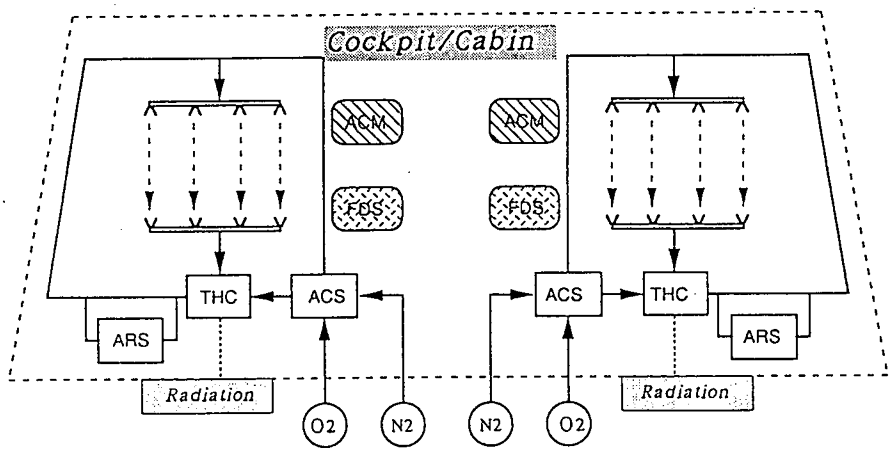


Figure 8. Structural concept of vehicle.

4.5 ECLSS

The ECLSS (Environmental Control and Life Support System) has a significant role to provide many passengers with a comfortable space flight. A redundant system concept is presented in Figure 9.



THC: Temperature and Humidity Control
ARS: Atmosphere Revitalization System
ACS: Atmosphere Control and Supply
ACM: Atmosphere Composition Monitoring
FDS: Fire Detection and Suppression

Figure 9. Environmental control and life support system.

4.6 Power Supply

The present SSTO vehicle will be equipped with two kinds of power supply systems, which are an electrical power system and a hydraulic power system. The electrical power system is comprised of Fuel Cell Systems that use cryogenically stored oxygen and hydrogen reactants, Reactant Storage and Distribution Systems and Electrical Control Units. The electrical power system produces all the electrical power required by ECLSS, cabin services and other onboard avionics equipment for the entire flight duration. For high intensity, but rather shorter duration power requirements that is called for by rocket engine gimbal actuation systems or by the body flap actuators, the hydraulic power system provides the necessary hydraulic power which is generated either by Auxiliary Power Units or by the rocket engine driven hydraulic pumps. In the case when the APUs are to be used, those will operated with hydrogen/oxygen fuel to ensure environmental friendliness. The APUs will be operated only during the ascent and descent phase of the flight operation.

5. Trajectory Analysis

5.1 Ascent Trajectory

A typical ascent flight has been simulated and a time sequence of flight conditions is shown in Figure 10. The four booster engines begin throttling when the vehicle reaches the acceleration level of 3 G about 100 seconds after lift-off when the vehicle gain has gone only a small downrange distance and is within safe distance for intact recovery at the launch site. The vehicle achieves the altitude of 200km in 6 minutes. More detailed analysis will be required to determine emergency flight plans in case of failure of the propulsion system.

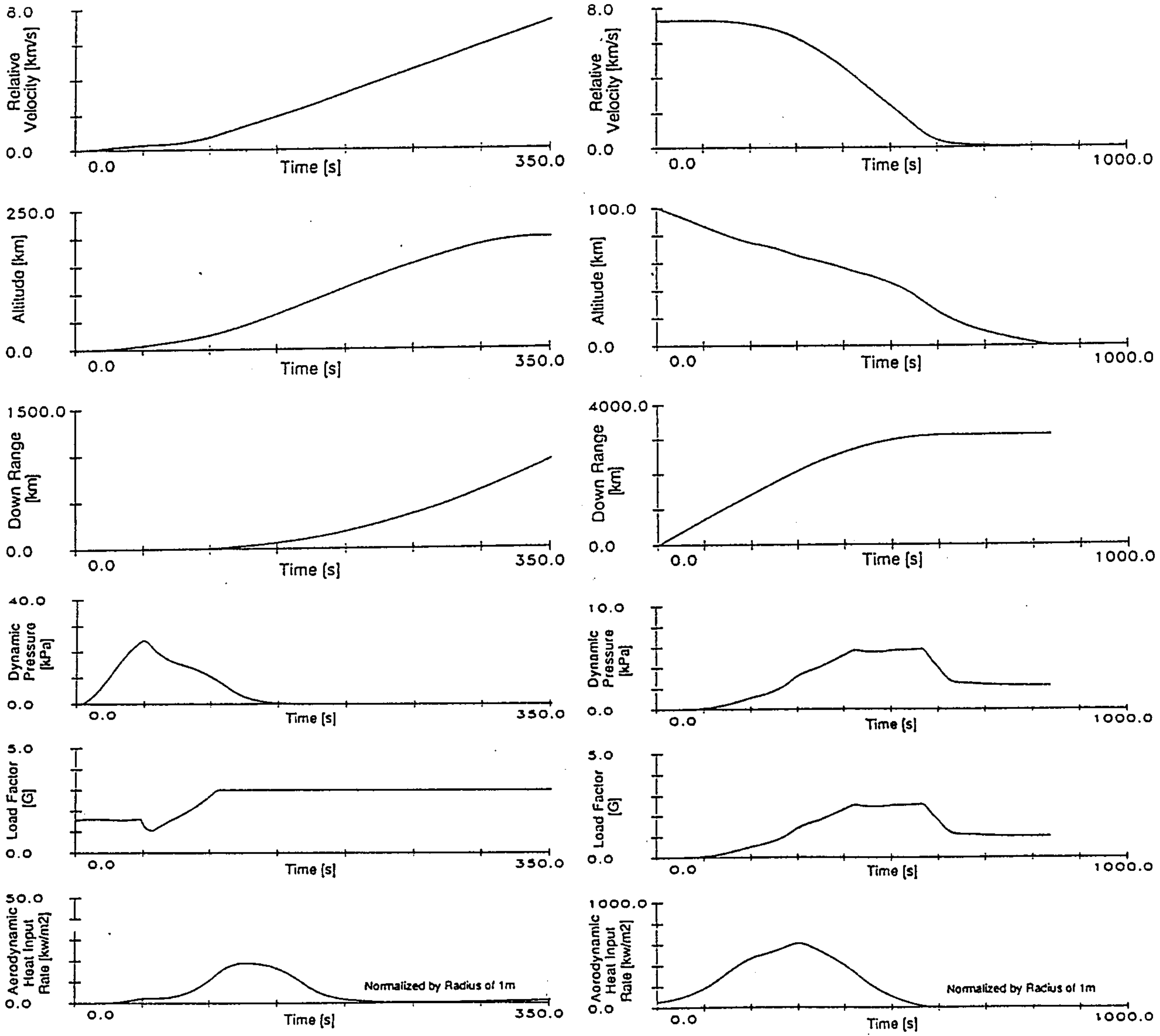


Figure 10. Simulated flight conditions (ascent: left and descent: right).

5.2 Reentry Trajectory

The guidance for the reentry trajectory simulation uses a conventional algorithm to control acceleration, which is widely applied to winged vehicles. Since the acceleration acting on passengers is limited to 3 G, the nominal reentry load factor including a safety margin is designed to be 2.5G. A typical reentry condition is shown in Figure 10. The low heat input due to the relatively small ballistic coefficient and the large radius of the base configuration makes it possible to apply very light-weight materials for thermal protection to the base surface.

One of the critical performance parameters for the present SSTO vehicle is the cross range capability. Our calculations predict that the cross range achieved by aerodynamic bank modulation will be a little more than 200km (Figure 11), which will limit orbit inclination and spaceport location, but will be large enough to assure emergency landing at medium latitude spaceports.

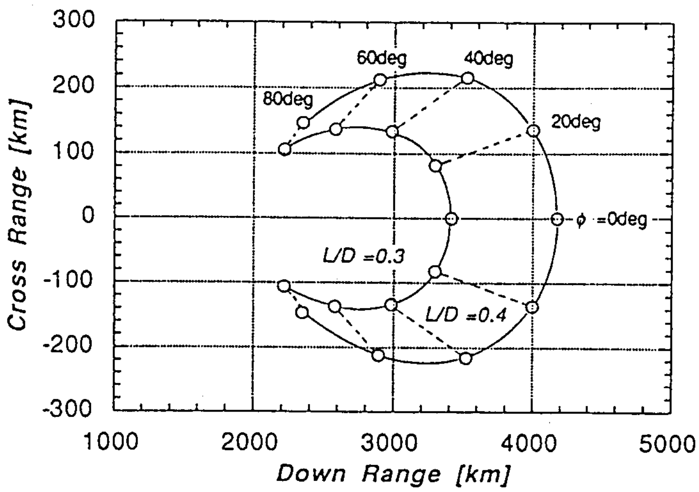


Figure 11. Range modulation capability.

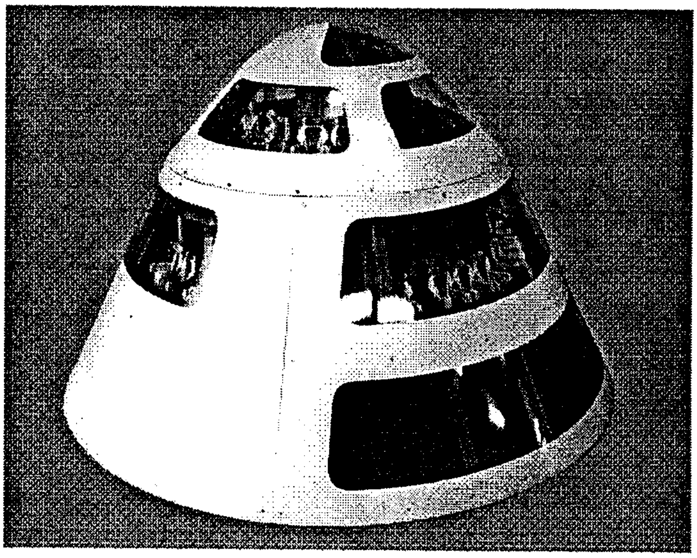


Figure 12. Upper part of scale model built for conceptual design study of an SSTO for space tourism.

6. Concluding Remarks

Studies on SSTO vehicles for commercialization of space tourism are about to start. The JRS transportation research committee was organized to define a vehicle model which was expected to be used for related studies as a reference vehicle. It held nine meetings discussing the feasibility of the vehicle design and available technologies over the past year.

As a preliminary result, a concept of a passenger vehicle to carry fifty passengers for a two orbit flight in low earth orbit has been developed. A scale model of the vehicle has also been built (Figure 12). However, many technology challenges were found at each meeting. In particular in the field of materials, we had to assume a 15% mass reduction from the current estimate for the structure through using advanced materials, such as CF/Epoxy/HC or MMC. Reviewing the current design and examining details of the scale model design, it seems to be possible to improve the vehicle design by further efforts.

Thus, we gradually understood that we will have to dump our old-fashioned way of thinking. We will conclude this paper with the question "Can enthusiasm for Space Tourism revive the 'stereotyped' approach of Japanese aerospace industries ?" Probably it will be answered "Yes" in the near future.

Acknowledgements

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DESIGN STUDY ON PROPULSION SYSTEMS FOR SPACE TOURIST CARRIER VEHICLE*

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Abstract

Propulsion systems for an SSTO (single-stage-to-orbit) type of space vehicle to be used for space tourism have been studied. Bell nozzle engines and liquid hydrogen and liquid oxygen propellants were chosen for this study to meet the targets of life time, reliability and maintenance frequencies assumed to be required analogous to present-day airline operations. Conceptual design and system analysis were made in terms of engine arrangement in the vehicle and intact abort capability, and a system was conceptualized.

1. Introduction

The Japanese Rocket Society (JRS) is studying space tourism as a near future space activity. Specifically, the JRS Transportation Research Committee is conducting a conceptual study of an SSTO type of reusable space vehicle to be used for space tourism. This paper is a part of the study, focusing on the propulsion subsystem.

According to a general guideline for the space tourism study (ref. 1), a typical spaceflight for the first phase space tour will be a three-hour orbital flight around the earth, and the flight frequency of the vehicle will be three hundred flights in a year. As for passenger accommodation, the maximum acceleration on the human body is 3 G, and atmospheric reentry of the vehicles is made in a base-first mode, to make the direction of G forces on passengers similar during both the ascent and descent phases of flight.

The reference vehicle designed by the research committee was a vertical take-off and landing SSTO vehicle whose propellants are liquid hydrogen (LH_2) and liquid oxygen (LOX) rather than advanced ones such as slush hydrogen (ref. 2). Requirements for the propulsion system emphasized operational aspects rather than engine performance, since operation of the reference vehicles aims at present-day airline operations. Engine handling and maintenance will be the most fundamental work to support airline-type operation of such space vehicles. It was suggested that "check before/after each flight" and "regular check per 6000 seconds or 12 flights" and "overhaul per 50000 seconds or 100 flights" are necessary for each engine life time which is 40 hours for 300 flights.

2. Engine Characteristics

Engine Configuration

There are two different types of rocket engine configuration considered as candidates for the main propulsion system of the vehicle under study. One is a multiple engine system of bell nozzle engines (dual-position), and the other is a plug nozzle engine.

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Although there is no major performance discriminator between bell nozzles and a plug nozzle, as pointed out by Ref. 3, a multiple engine system with bell nozzles has been adopted for this study, considering general criteria for vehicle design, such as:

- simplicity of operation during engine-out contingency,
- roll control capability provided by gimballing the engines, and
- thrust vector control by gimbal mounting of engines.

Engine cycle

For multiple engine systems, characteristics of each engine such as performance, cost and maintainability will critically affect the performance and maintainability of the systems. Especially in this case, the operational aspect of performance characteristics will be more important than in the case of expendable rockets. In this respect, expander- derived engine cycles which maintain low power cycle temperatures and minimize system complexity are considered to be the best for the propulsion system under study. Although staged-combustion cycle engines are known to offer higher specific impulses and better envelope advantages than expander-derived engine cycles due to higher chamber pressure, their technology is too expensive to satisfy the requirements for low life cycle cost operation like airplanes. On the other hand, specific impulse of expander cycle engines is expected to increase almost as high as that of staged-combustion engines, as discussed in the following.

Prospective improvement of existing engines

We will discuss a little further the justification of our selection of engine cycle in connection with design analysis of optimum sizing of engines. Figure 1 shows some results of our analysis on the performance of several kinds of expander cycle engines based on existing technology. A critical issue of this type of engine is to increase chamber pressures high enough to keep high specific impulse at sea level.

In Figure 1, the sea level specific impulse is shown as a function of chamber pressure for three engines designated as; Expander, Expander bleed and Augmented expander. The EPS is abbreviation of expansion area ratio. The Augmented expander cycle proposed by Aerojet Propulsion Division (ref. 4) is a typical engine cycle in which flow enthalpy to drive turbines are augmented by additing chemical energy with combustion products to the coolant exiting the chamber. Two cases with different expansion area ratio are shown in Figure 1. The Expander bleed cycle has been based on LE-5A engine (ref. 5)

Figure 2 shows our result of analysis of turbine pressure ratios and chamber pressures for an augmented expander cycle engine operating at three turbine temperatures. Each curve indicates it is not efficient to increase the chamber pressure beyond a certain level because turbine pressure ratio increases more rapidly. In this respect, a maximum engine chamber pressure of 10 MPa will be enough to achieve high specific impulse at sea level.

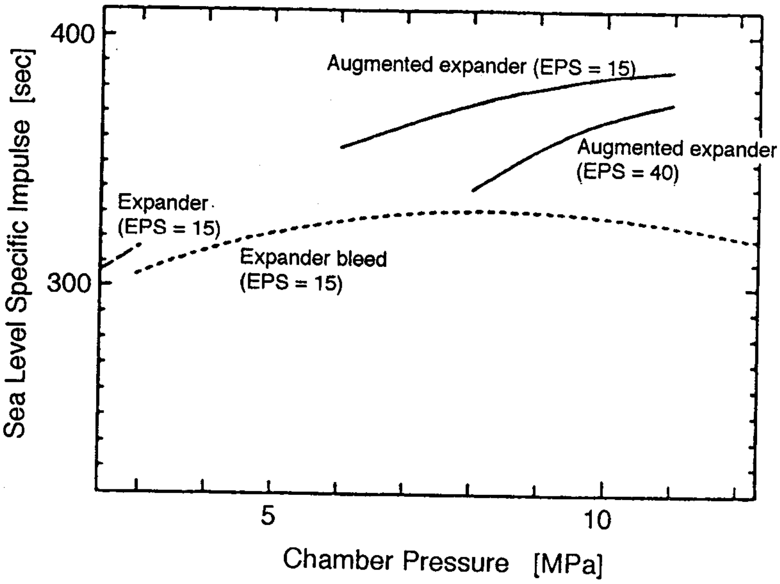

Figure 1. Performance of expander cycle engines to be built with existing technology.
(Thrust level is 70 tonf.)

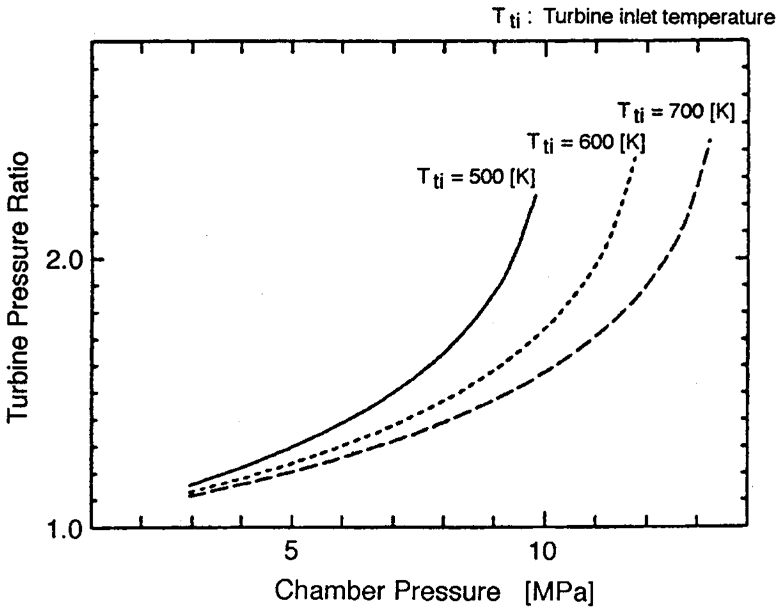

Figure 2. The cycle limits of augmented expander cycle engine of conventional technology level.

Characteristics of candidate engines

To improve the overall performance of a propulsion system consisting of bell nozzle engines whose performance changes with altitude, two types of engines: booster and sustainer engines will be used. The expansion ratio for the booster engine was selected to be 15 to derive maximum thrust at liftoff. The sustainer engine will be provided with an extendible nozzle, and nozzle expansion ratios are 80 and 40 at fully extended and retracted positions, respectively.

The characteristics of these candidate engines have been based on the LE-7 engine, about 80 % level of which is assumed for the thrust levels in order to assure reliability and a life cycle to meet the operational requirements for space tourism. Thus, the chamber pressure was determined to be 10 MPa at a mixture ratio of 6. Other characteristics of the engines are summarized in Table 1.

Table 1 Characteristics of candidate engines

Booster engines			
Nozzle expansion area ratio		15.	
Nozzle contour		90% bell	
Thrust	sea level	73.9 tonf	
	vacuum	80.6 tonf	
Specific impulse	sea level	381.0 sec	
	vacuum	415.5 sec	
Isp efficiency*		0.968	
Thrust to weight ratio		77.1 : 1	
Sustainer engines			
Nozzle expansion area ratio		40.	80.
Nozzle contour		56% bell	75% bell
Thrust	sea level	65.6 tonf	-
	vacuum	83.8 tonf	87.8 tonf
Specific impulse	sea level	338.2 sec	-
	vacuum	431.8 sec	452.7 sec
Isp efficiency*		0.952	0.968
Thrust to weight ratio		74.3 : 1	

* Isp efficiency = C* efficiency × C_f efficiency

Engine Maintenance

The engines are required to have long lifetime and ease of operation similar to those of current airliners. To obtain this capability, it is important to reduce the number of parts that directly affect the engine life cycle. Table 2 shows our goals for the numbers of life-critical engine parts in comparison with those for engines of passenger airliners and conventional rockets.

Table 2 Numbers of Life-critical Engine Parts

	Our goals of the reference vehicle	Typical jet-engine	conventional rocket engine
Life cycle of critical parts	300	about 20000	about 10
Numbers of life-critical parts	max 30	20 - 30	50 - 300
Numbers of Total Parts	1000 - 5000	about 10000	1000 - 5000

3. System Analysis

Arrangement of Booster and Sustainer Engines

To maximize the performance of a multiple-engine propulsion system, we have to choose an optimum combination of the candidate engines: booster and sustainer engines. The design requirements are to attain a required orbital velocity at the minimum mass penalty of engines and propellant consumption under the constraint of a maximum acceleration of 3G. In general, booster engines will burn only in the early phase of the ascent, while sustainer engines will be used for all phases of the ascent. Selection of the number of each type of engine, and general arrangement of engines on the base of the vehicle are critical design considerations for the multiple engine system in this study.

Table 3 summarizes four candidate cases of engine combination together with the main results of calculations. For each case, it was possible to inject 66 metric tons into low-earth orbit. Case C, a combination of four booster engines and eight sustainer engines, put the largest mass into orbit. It is noted that the largest mass on orbit does not necessarily imply the largest payload, since it includes payload, dry vehicle and propellants. This table also shows the results of engine weight estimation (ref. 6). As a result of investigation, it is ascertained that the case C which has a largest capability of injection mass into orbit will be able to put the largest payload. If the actual weight of the extendible nozzles of sustainer engines are heavier than the estimated value, dominant position of the case C will be break.

Table 3 Engine Combinations and Payload Capability

Case	Engine Characteristics							Orbit Injection Capability		Total Payload Increment [ton]
	Engine Type	Number of Engines	Isp vacuum [sec]	Thrust vacuum [tonf]	Thrust-to-Weight	Total E/G Weight [ton]	Weight Penalty [ton]	Injection Weight [ton]	Gain [ton]	
A	Booster	8	415.8	71.1	76.8	12.674	0	67.614	0	0
	Sustainer	4	431.8-452.7	63.1	61.0					
B	Booster	6	415.7	72.5	76.9	13.147	- 0.473	68.854	1.240	0.767
	Sustainer	6	431.8-452.7	64.3	61.3					
C	Booster	4	415.5	73.9	77.1	13.639	- 0.965	69.589	1.975	1.010
	Sustainer	8	431.8-452.7	65.6	61.6					
D	Booster	4	415.7	72.7	76.9	12.812	- 0.138	66.886	- 0.728	- 0.866
	Sustainer*	8	440.9	66.3	77.5					

Note) * fixed expansion ratio of 40, E/G : Engine

Initial thrust-to-weight ratio

On designing the vehicle shape, we prioritized passenger accommodation rather than aerodynamic characteristics to maximize payload mass. As a result, the vehicle has been designed to be of a short and stocky shape with relatively high aerodynamic drag. The only variable which minimizes the total losses caused by aerodynamic drag and gravity during ascent is the initial thrust-to-weight ratio at lift-off. If acceleration is increased higher, aerodynamic drag will increase, while gravity loss will decrease. Figure 3 shows results of calculations on the relation of mass in orbit vs. initial thrust-to-weight ratio. In this calculation, the penalty of higher acceleration due to increase of engine mass is considered, while other weights are assumed to be constant. The maximum payload is about 7.5 ton when thrust /weight is 1.5, which is 1.1 ton larger than when the thrust-to-weight ratio is 1.3. Thus, 1.5 is chosen as the initial thrust-to-weight ratio.

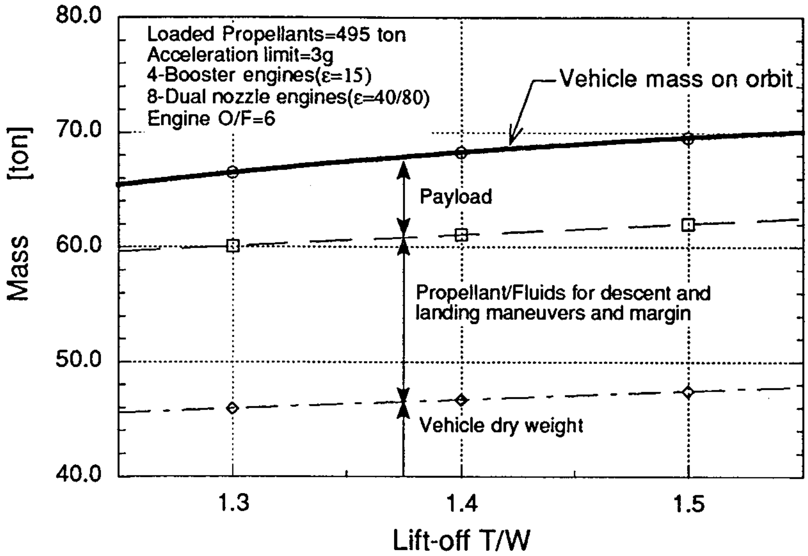

Figure 3. Mass on orbit vs. thrust-to-weight ratio at lift-off.

Abort Capability

Intact abort capability in case of engine failure is one of the most important requirements for an aeroplane-type operation SSTO (ref. 7). To satisfy this requirement, the thrust-to-weight ratio when an engine or engines fail must be greater than one so that the vehicle can continue to climb and burn out its residual propellants and land safely.

If the thrust-to-weight ratio at lift-off is assumed to be 1.5, twelve engines are required for the reference vehicle. The allowable number of malfunctioning engines for a twelve-engine system is four. In this case, if a normally operating engine has to be shutoff to compensate thrust imbalance due to failure of an engine, the number would still be two, which means the abort capability of this case is very high.

4. System Concept

Engine combination and operation

The lift-off weight of the reference vehicle is estimated to be about 550 ton(ref. 2). As discussed previously, it will be assumed that the thrust-to-weight ratio at lift-off is 1.5. It was concluded that the case C which put the maximum mass into orbit could be the best system to maximize the payload. Therefore, the combination of four "booster" engines and eight "sustainer" engines has been selected as the final design. As discussed above, this engine combination has a very high margin of abort capability.

For ascent, all engines are burned at lift-off and then some are subject to shutoff and throttling so that the acceleration should not exceed 3G. For descent, four booster engines are ignited but two of them wait in idling mode (about 5 % of rated thrust) preparing for engine failure. Prior to landing, the vehicle weight is about 60 tons. The necessary engine throttling level is about 30 % allowing for the engines operating in idling mode.

Figure 4 shows the time history of specific impulse and altitude during ascent of booster and sustainer engines in the combination as in case C in Table 3. Figure 5 shows the nominal history of thrust and acceleration for the same case. This figure also shows that if the engines have about 30%-of-maximum thrust throttling capability, the maximum deceleration level for passengers is less than 0.5 G when the booster engines cut off.

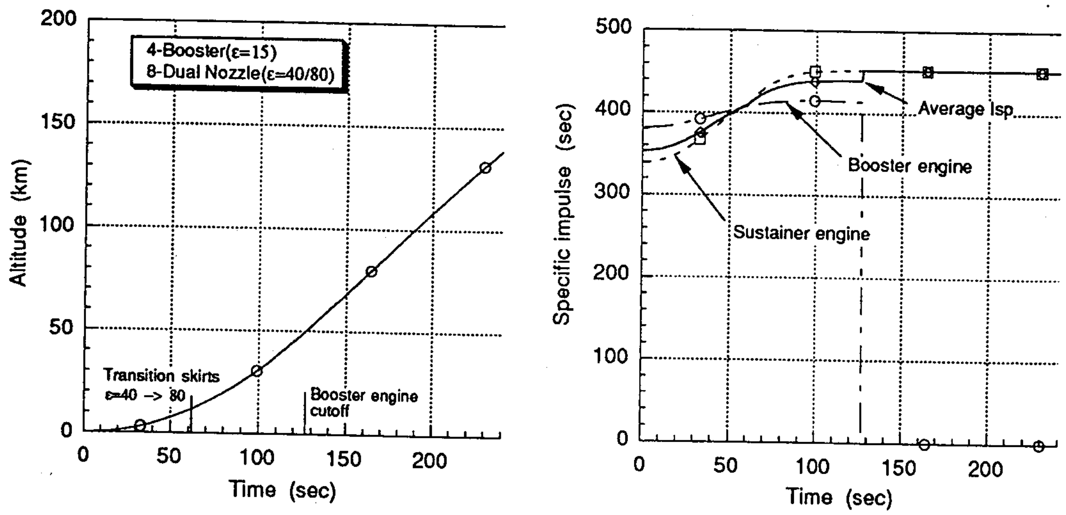

Figure 4. Specific impulse of engines (right) and altitude (left) during ascent.

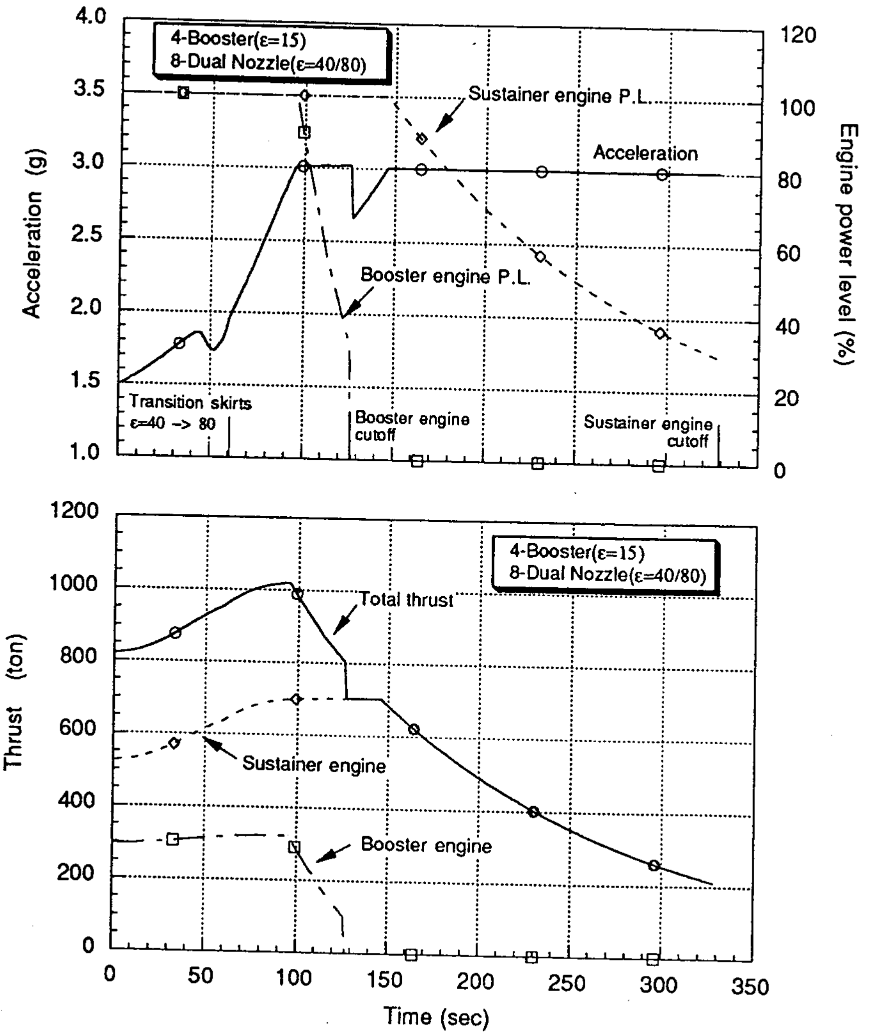

Figure 5. Thrust and acceleration during ascent for Case C in Table 3.

Tank and Propellant Feed System

The orbital stay time of the reference vehicle is from 3 to 24 hours. Therefore it is important to maintain liquid propellants and their temperature, and to feed propellants to engines so that they can restart reliably before descent. But the main tank is too big for this. So auxiliary tanks are necessary for coasting and restart. These tanks are located under the LOX tank and insulated to maintain the propellants for 24 hours or more. A baseline schematic diagram of the tank and propellant feed system is shown in Figure 6. For LH_2, auxiliary tanks are double because of vehicle space. During the ascent phase, all main engines and auxiliary tanks are fed propellants from the main tanks. And during the descent and landing phase, the 4 booster engines (2 engines waiting in idle mode) use propellants from the auxiliary tanks.

Tank Pressurization and Vent System

A baseline schematic diagram of the tank pressurization and vent system is shown in Figure 7. Both main tanks are pressurized with ambient temperature helium (GHe) from the ground facilities prior to engine start and during the engine start transient. During the ascent phase after lift-off, the LH_2 main tank is pressurized with gaseous hydrogen (GH_2) tapped from the engine and the LOX main tank is pressurized with gaseous helium (GHe) which is stored in cryogenic helium (CHe) bottles mounted in the LH_2 main tank and warmed by the engine heat exchanger. The LH_2 and LOX tank pressures are controlled by on/off actuation of simple shutoff valves. After engine cut-off, both tank pressures will be reduced and controlled by on/off control valves (FVRV/OVRV) to keep propellant temperatures low while on orbit. Before descent, the auxiliary tanks are pressurized with GHe, which is supplied from the GHe bottles, before engine restart and during start transient. After engine start, auxiliary tanks are pressurized in the same manner as in ascent. Both tank pressurization modules and the pressure control module of CHe have redundant units. The FVRV/OVRV also operate for venting before launch, protecting the tanks from rupture.

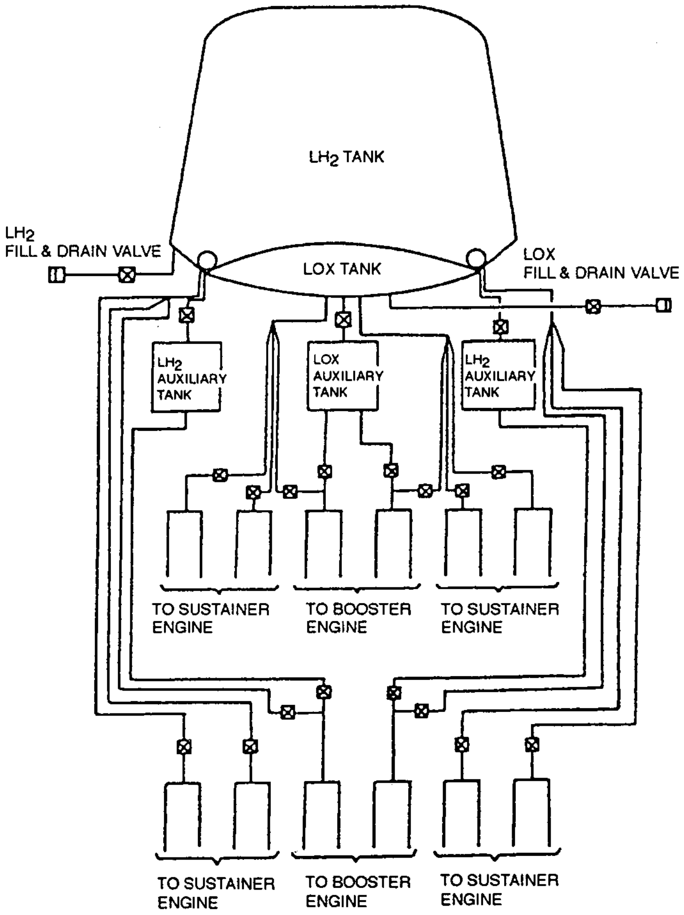

Figure 6. Schematic diagram of the tank and feed system.

Reaction Control System

Considering safety for passengers and ground operators, gaseous oxygen and hydrogen (GOX and GH_2) instead of toxic gases are used as propellants of the Reaction Control System (RCS). The RCS is used mainly in the period from engine cut-off to engine restart. In this time, a total impulse is given of about 4.2×10^6 N s (ref. 1). Its baseline schematic diagram is shown in Figure 8. Considering weight and mounting space, the RCS will consist of boost pumps, a set of accumulators for liquid and gaseous propellants, gas generators, regulators and a set of GOX/GH_2 thrusters. The main characteristics of the GOX/GH_2 thruster are assumed as follows.

- Thrust	: about 7000 N
- Chamber Pressure	: about 1.5 MPa
- Mixture Ratio	: about 6
- Specific Impulse	: 320 sec.

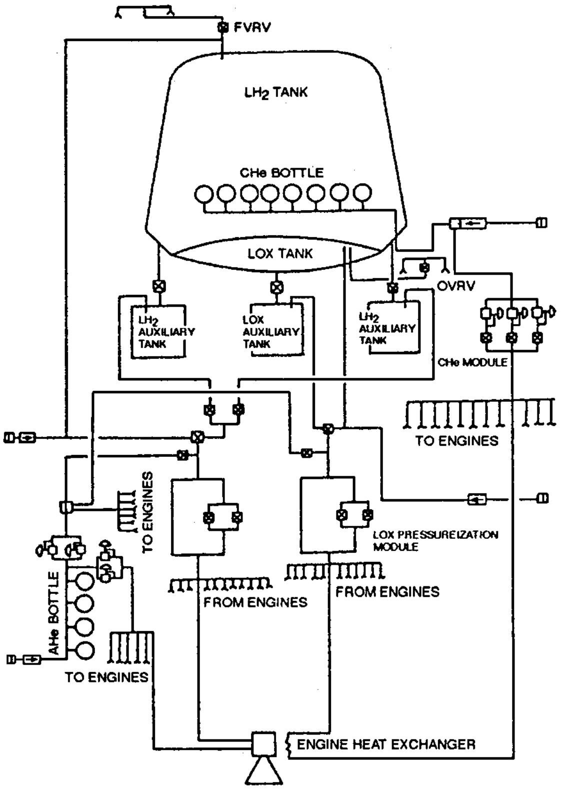

Figure 7. Schematic diagram of the tank pressurization and vent system.

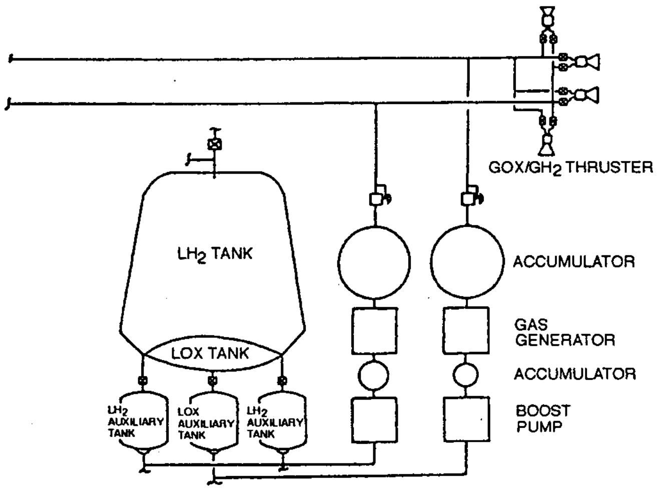

Figure 8. Schematic diagram of the reaction control system (RCS).

5. Considerations on Further Study

This stage of the vehicle study has been concerned mainly with conceptualization of each subsystem, so that the concept of the propulsion system will have to be improved during the future work on vehicle integration. The following questions are left for future study in connection with vehicle integration design.

Vehicle Integration

As far as propulsion is concerned, the estimate of the vehicle mass summarized in Ref. 2 does not reflect actual design data but is empirical data of expendable vehicles. The estimated mass should be revised considering the uniqueness of vehicle geometry and special design requirements of airline-type operation.

The base-first atmospheric reentry raises issues of integration of the propulsion system with the vehicle, since additional provision for thermal protection of the engines will be required. The preliminary design of the vehicle provides a sliding hatch to cover each nozzle exit(ref. 2). The geometrical shape of the bottom is now determined by aerodynamic reasoning, but has not yet been examined from the standpoint of its impact on rocket performance.

Presently, each engine is assumed to be provided with a gimbal mounting movable in pitch and yaw directions. Further study should look into the possibility of reducing the number of mechanical equipments

Operation

As noted, this propulsion system has sufficient design margin of abort capability, and is also provided with high initial thrust-to-weight ratio. This design feature is supported by low engine mass estimation, but will be changed if the actual mass of the engines differs from the estimates used in this study.

For the prelaunch operation, the system concept is based on conventional launch vehicles rather than aircraft. It is admitted that the post landing refurbishment procedure which will be crucial to reusable space vehicles in frequent operation has not yet been conceptualized. The facilities to support ground operation have not been studied in detail either.

In future studies, we expect improvement of the propellant feed and pressurization system design, according to more detailed requirements definition based on the individual engine specifications.

6. Conclusions

As a part of a preliminary study of an SSTO vehicle for space tourism, a combination of expander-derived engines to use liquid hydrogen and liquid oxygen has been studied. To feature space tourism, the vehicle was designed to be of blunt body to enter the atmosphere in a base-first attitude, and passenger accommodation has been prioritized in terms of vehicle design and maximum acceleration.

The concept proposed here is a system consisting of four booster engines and eight sustainer engines. Booster engines designed to have high specific impulse at low altitude will be used during the initial phase of ascent, and sustainer engines which will be used through all ascent phases are provided with extendible nozzles to achieve higher performance at high altitude.

The initial thrust-to-weight ratio is determined to be 1.5, which maximizes the payload into orbit. Therefore, shutoff of four engines at most can be allowed in case of abort. However, more detailed study will be required to finalize the design, especially in the field of operational requirements which are not well defined at the present.

Acknowledgments

The authors are grateful to the JRS transportation research committee for valuable discussions.

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LIQUID HYDROGEN INDUSTRY:A KEY FOR SPACE TOURISM+

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Abstract

Features of liquid hydrogen industry as a key industry to support an aircraft type of space transportation system to be operated for space tourism have been studied on the base of a prospective production model of the space vehicles and an operational concept of space tourism business.

1. Introduction

The current commercialization of expendable rockets and satellite communication services depends on space technology developed by governments which monopolized space activities since the sputnik era. Remembering that planned economy is being replaced by free economy, we can expect a new context of space commercialization demanded by other fields than the current space business. One of such a business will be space tourism supported by a true space transportation system which will be operated like commercial airlines.

The key issue that makes the true transportation system uncertain is the future of reusable space vehicles which can be operated like aircraft. The Space Shuttle, which was proposed as the National Transportation System has failed in demonstration of low cost transportation by reusable vehicles. Experiences of Space Shuttle indicate that the low cost operation of airline systems cannot be achieved by winged vehicles without improvement of complex launch operation and expendable hardware. The recent demonstration of DC-X and development of related technology seem to make SSTO feasible.

The current airline systems make a global infrastructure for transportation. The true space transportation system will be designed on the base of this infrastructure. In this respect, air-traffic control systems, airport service for passengers and cargo and ground facilities for maintenace and operation are expected to support more or less the space transportation systems. An only exception will be propellant supply facilities which will handle a large amount of liquid hydrogen. This paper is intended to clarify the characteristics of the propellant indutry to prepare for the new space transportation system.

2. Concept of Space Tourism

Space tourism will be defined as spaceflight for the general public. Since it is necessary for tourism that passengers can pay the fee for each and the service should be conveniently provided by travel agents, the spaceflight for space tourism will be significantly different from the past spaceflight which have been made exclusively by qualified astronauts selected under a strict standard. The key issue to make the difference is the vehicles to be used. The vehicles that serve for space tourism will be featured as follows.

1) Vehicle manufacturers will participate in the economic activities of space tourism. The vehicles will be built on a production line and avail-able to commercial transportation operators.

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2) The procedures for operation and maintenance of vehicles will be standardized and the qualified operators are responsible for implementation of transpotation safety.
3) Airports will provide space transportation systems with common services for airlines at reasonable cost.

Table 1 Cost Targets of Space Tourism

	Wide-bodied jet	Passenger launch vehicle
Production run	1000	50
Price (hundred million Yen *)	200	1000
Flights per year	720	300
Lifetime (years)	20	10
Amortization ** (ten thousand Yen)	220	4300
Fuel cost per flight (ten thousand Yen)	200	1600
Miscellaneous cost (ten thousand Yen)	200	2000
Total cost per flight (ten thousand Yen)	620	7900
Passengers per flight	300	50
Cost / person (ten thousand Yen)	2.1	160
Passengers per year	200 million	750,000

* : 100 Yen is approximately 1 US $.
** : assuming 5% interest rate.

Before discussing features of the liquid hydrogen industry, we will explain about general features predicted for the space tourism. Table 1 (ref. 1) is a representative cost targets for space tourism to show an example of requirements imposed on transportation systems to be used for space tourism. In Table 1, such a space vehicle is compared with typical wide body aircraft. We will examine individual figures in this table from the standpoint of their application for a preliminary demand analysis of liquid hydrogen. The number of 50 vehicles is assumed to be the minimum of this kind of production model, so that the general figures shown by this table will be considered moderate. The price of each vehicle assumed here will be highest and should be lower than 100 bilion Yen when more experiences are accumulated in this field.

The number of flights per year, 300 are required for each vehicle. Considering 20% of off-service days in a year for maintenance, this figure assumes each vehicle makes one flight every service day, less frequently than a Wide-bodied Jet that makes two flights everyday through a year.

Total cost required for each flight is divided into three categories; amortization, fuel and miscellaneous. The sum of these costs is 79 million Yen. From an economic point of view, the number of passengers and the fee have to be determined to cover this cost. An example shown here is for 50 passengers to pay 1.6 million Yen for each. It should be noted that the price and life of a vehicle which affect the amortization, depending on the engineering efforts. So far, no serious study was not made for development of such a vehicle.

3. Vehicle Model

In Table 1, most of the vehicle characteristics were given as a statistical data of a transportation system, except for the numbers of passengers and the cost of fuel per flight. To estimate quantitative demand of liquid hydrogen, based on these figures, design data of some vehicles will be used. Actually, there are few choices of vehicles which have potential capability to carry fifty human passengers by propellants worth 16 million Yen.

Table 2 shows selected mass properties of three vehicles of SSTO which were designed conceptually (ref.2, 3 and 4). Payload mass of the JRS study vehicle includes fifty passengers and the crew members and necessary accommodations. If the same mass proportion is applied for payload mass of Phoenix, its passengers will be calculated to be thirty two. Then, propellants mass per passenger is larger for Phoenix than JRS study. However, Phoenix reserves additional mass for the pilot module which seems to give a conservative mass estimation. The BETA is a well-known vehicle, although its mass breakdown for passenger accommodation is not available.

Table 2 Comparison of SSTO Mass Properties

Vehicle	BETA	Phoenix C	JRS Study
Payload (ton)	4	4.77	7.51
Passengers (persons)	-	32	50
Lift-off mass (ton)	131.5	206	550
Propellants mass (ton)	117.5	183.8	494.9
Mixture ratio (Lox/LH_2)	5.5-8.0	7-13	6

Because of the convenience of communicating with the concept developers for technical detail, we have chosen the JRS study model as a reference vehicle to estimate the operation cost required for the passenger vehicle in Table 1, and summarize the propellants consumption data in Table 3 for further study.

Table 3 Propellants Consumption and Reference Vehicles Operation Model

Propellants mass per flight:	494.5 ton
Liquid Oxygen	424.2 ton
Liquid Hydrogen	70.7 ton
Total opertional fleet	50 vehicles
Flight frequency for each vehicle	300 flights per year
Total flights in a year	15,000 flights
Spaceports location	World wide

According to the cost requirement shown in Table 1, the cost of 424.2 ton of liquid oxygen and 70.7 ton of liquid hydrogen of this model should be 16 million Yen. Since the current prices of both liquids are almost same if measured per volume, the target prices of both liquids will be ten Yen per litre for each, which is nearly half of the current price of these liquids in the U.S.

4. Scenario of Fueling Procedures

The consumers of liquid hydrogen and oxygen are space transportation operators at launch sites of major airports, as described later. Fueling operation for rockets used to be more time-critical than for aircraft in order to avoid loss of cryogenic propellants due to incomplete thermal insulation of the vehicle tank system. For the advanced space vehicle for space tourism, maintenace procedures will be simplified and overall procedures will be so designed to be repeated on a daily base. However, at the last moment of launch operation starting for chilldown and filling propellants, the situation will not be improved so much from that of Space Shuttle whose procedure of filling propellants takes about two hours including ten minutes for chilldown. The advanced passenger vehicles will be designed to make the required time for fueling procedure shorter than one hour, which means the transfer speeds of liquid hydrogen and oxygen should be increased a little faster than those for Space Shuttle.

Figure 1 shows an image of a spaceport provided with three vehicle spots where passenger boarding and ground support operation will be performed. A vehicle will return to one of the spots exactly in the same way as it is placed for lift-off. Ground operation will be started for the next flight as soon as it lands on the spot. Probably fueling pipelines will be connected soon after de-planed.

Spaceport Facility

Different from traditional thinking, a preliminary study (ref.4) suggests that the launch sites for space tourism should not be remote from populated cities but attached to or a part of major airports, since vehicles for space tourism to be designed to assure passenger safety by more strict safety standard than exisiting safety standards used for ammunition and traditional space rockets.

When fifty vehicles are to enter operation, about ten spaceports will be required to provide services to their flights. The fifty vehicles will be owned by more than ten operating companies. As far as the propellant supply is concerned, in the early phase of space tourism, four to five flights will take place at each spaceport everyday. In this case, each spaceport will be required to handle 4000 kl (280 ton) of liquid hydrogen and 1500 kl (1600 ton) of liquid oxygen for net loading in vehicles everyday.

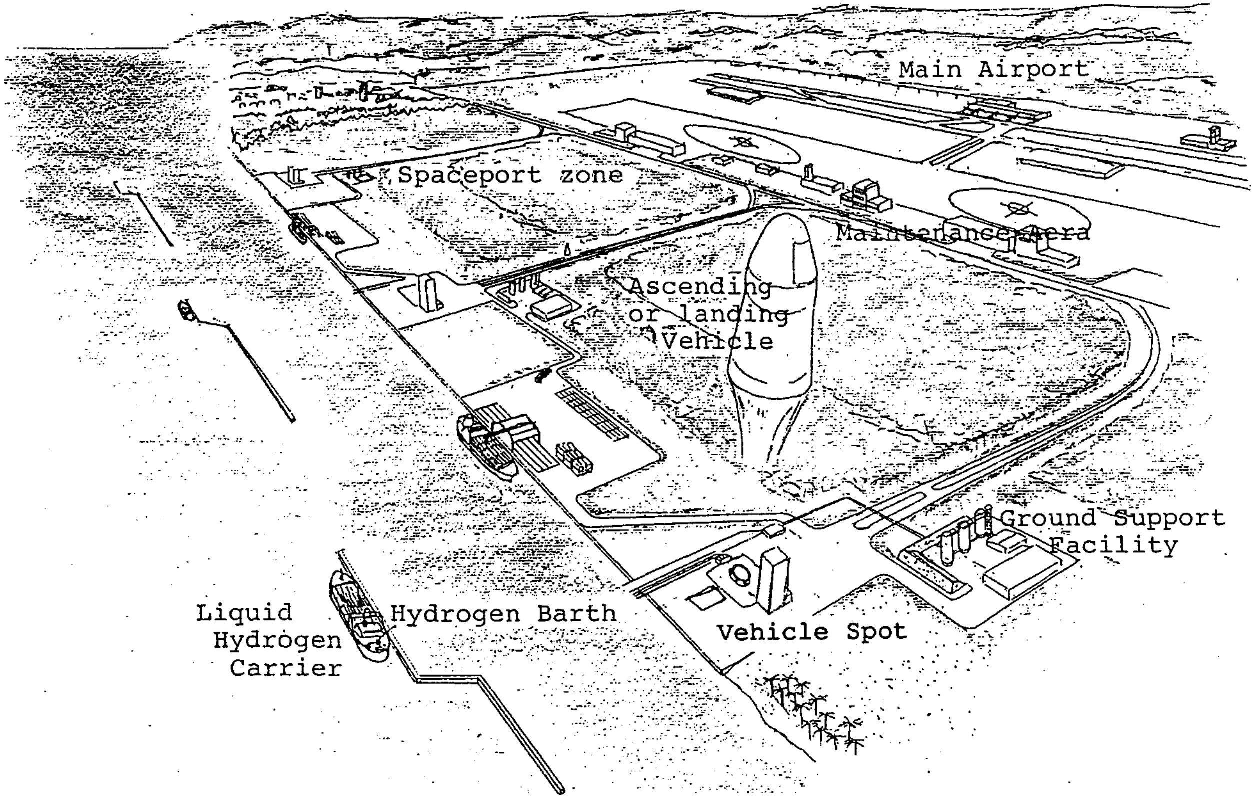

Fig. 1. An image of a spaceport attached to a major airport. (Ref. 5.)

Liquid Hydrogen Technology

In this paper, liquid hydrogen supply will be mainly discussed, since the present level of production of the hydrogen industry is too low to satisfy the predicted future demand while the oxygen industry is already a well established industry. In Japan, for example, annual production of hydrogen is equivalent to 7000 kl (500 ton) of liquid hydrogen, and the one third of which is used for rocket propellant. The full capacity of production facilities is equivalent to 22000 kl of liquid hydrogen which correspond to 60 kl (4.2 ton) per day, only 6 % of demand for a single vehicle operation previously discussed. As for the cost, the present cost of liquid hydrogen in Japan is 40 times higher than the taget cost in Table 1. (Data as of 1993).

5. View of Liquid Hydrogen Industry

Although being considered to contribute and benefit from development of space tourism, the liquid hydrogen industry stresses evolutionary growth of production, being concerned about the risk of investment in the future of the great but unknown market.

An example of a supplyer's plan of progress of liquid hydrogen supply for the space tourism industry is shown by eight phases defined as follows;

1. Development of vehicles.
2. Test flight.
3. Three flight per year.
4. Ten flights per year
5. Twenty flights per year
6. Thirty six flights per year.
7. Seventy flights per year.
8. Daily flights through year.

In case that one flight requires 70.7 ton of liquid hydrogen, the total quantity of liquid hydrogen to be loaded on vehicles in a year of each phase has been calculated, as shown by Table 4.

Table 4 Phased Growth of Liquid Hydrogen Supply

Phase	Net loading quantity of liquid hydrogen** (ton/year	ton/day	1000kl/h)
1	*	*	*
2	*	*	*
3	220	0.6	0.36
4	710	1.95	1.17
5	1420	3.90	2.35
6	2545	6.98	4.19
7	4950	13.56	8.13
8	25805	70.70	42.42

* At these phases, demands will be within the existing production capacity. The present production capacities of the U.S., Europe and Japan are 200, 20 and 5 ton/day, respectively, as of 1993.

**Three units indicate the same value for each phase.

6. Demand for liquid hydrogen during vehicle development

If the vehicles are assumed to be produced in line like commercial aircraft, engineering works such as design, subsystem tests, assembly and flight tests will be necessary before certification of a production model is accomplished. Considering the quantity of liquid hydrogen for each phase, the scenario described above can be applied for vehicle development activities. This development period is especially important for both vehicle industry and liquid hydrogen industry to establish a reliable relation of supply and demand of liquid hydrogen. Experience during this period will be useful for planning a large scale operational hydrogen supply systems, and vehicle development activities

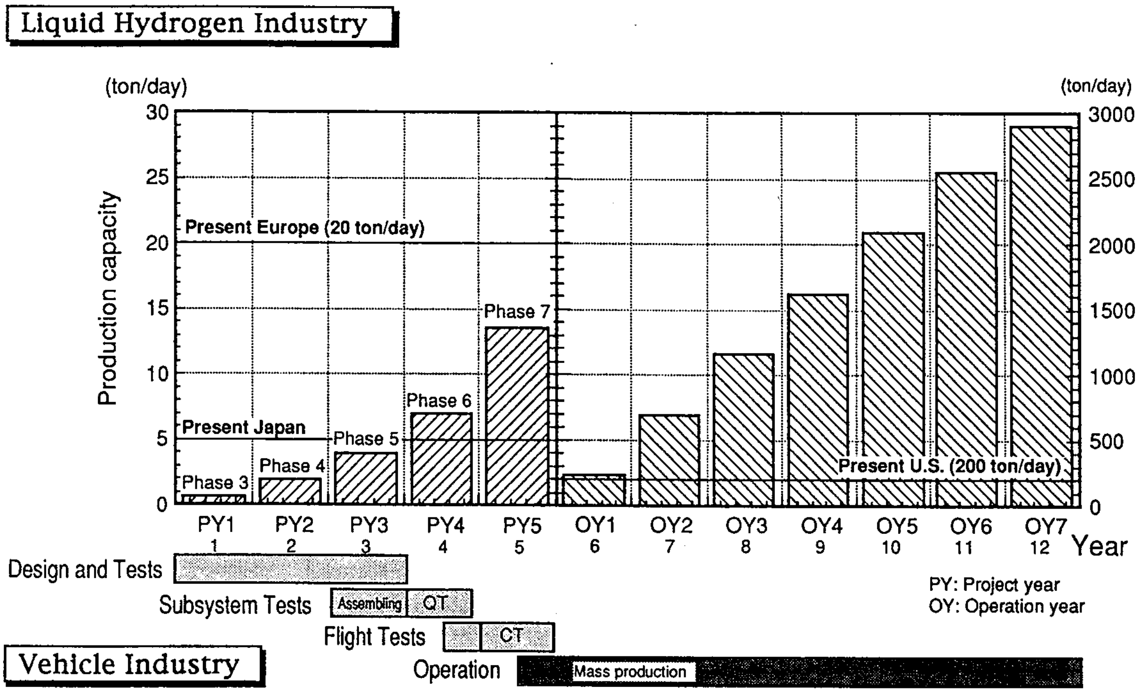

Fig. 2. Evolutionary growth of hydrogen industry to meet vehicle development.

through certification of the vehicle will assure the successful flight operation that will require large scale hydrogen facilities.

Although length of each phase is not specified for the liquid hydrogen scenario, a constant step-up of production capacity will be desirable. On the other hand, there will be another requirement for time schedule of vehicle development which determine the demand of liquid hydrogen. It is the most desirable that the demand increases keeping a good balance with the growing hydrogen supply shown by the scenario. Figure 2 is a diagram to show liquid hydrogen supply in a scale of net loading capacity of liquid hydrogen vs. vehicle development time schedule. The liquid hydrogen supply shown by the bars is based on a hypothetical time schedule of a vehicle development prepared to show an exmple of relation between increases of demand and supply of liquid hydrogen. In this case, the increase rate is logarithmically uniform. In an actual case, however it will depend on largely on the certification flight requirements that is to be determined.

7. Forecast of Hydroogen Demand in Operational Phase

Once mass production started, the demand of liquid hydrogen will rapidly increase in proportion to vehicle and flight numbers. Table 5 shows a result of a case study of operational vehicle production. According to the study, the fifty vehicles are assumed to be produced in seven years, that is, 0.6 vehicle is delivered every month to globally deployed operators who are based on each home spaceport. By the end of seven years of production, the global liquid hydrogen supply capacity will be increased to 3535 ton/day.

The present air transportation system will be a basic model for deployment of spaceports for space tourism on a global base in three regional zones; the eastern Asia and Oceania, the north and south America and the Europe and Africa. Table 5 also shows a scenario of opening spaceports in these regions.

Table 5 Growth of Liquid Hydrogen Demand for Space Tourism Vehicles

Year			OY 1	OY 2	OY 3	OY 4	OY 5	OY6	OY7
			Operational phase (mass production)						
Number of Vehicles (worldwide)			4	12	20	28	36	44	50
Frequency of flights (flights/year/vehicle)			300	300	300	300	300	300	300
Net loading quantity of liquid hydrogen (ton/day)	Worldwide total		232	697	1162	1627	2092	2557	2905
	Spaceport A	(Asia)	116	174	232	271	261	320	363
	Spaceport B	(US1)	116	174	232	271	261	320	363
	Spaceport C	(US2)		174	232	271	261	320	363
	Spaceport D	(US3)			232	271	261	320	363
	Spaceport E	(EU1)		174	232	271	261	320	363
	Spaceport F	(EU2)					261	320	363
	Spaceport G	(Russia)				271	261	320	363
	Spaceport H	(Oceania)					261	320	363

In spite of the forecast shown by the case study, the U.S. and Canada are considered to be the best for the first operational base for vehicle operators, since even now the price of liquid hydrogen is much lower than in Japan and Europe and very close to the target cost. The high price and low production featuring the Japanese liquid hydrogen industry are due to high electricity cost and unnecessarily strict regulation for transportation and storage. If liquid hydrogen is transported by large vessels specialized to the purpose, like LNG carriers, even now the suggested quantity of liquid hydrogen propellant will be supplied on a global base by commercial suppliers.

The main field of a large scale hydrogen use under study is clean energy to substitute carbon fuel for terrestrial use in large scale. However, demand for hydrogen as clean energy is a matter of the future of humankind which is too general to be a driving force to motivate technology development for large scale liquid hydrogen supply systems. On the other hand, demand of rocket propulsion for space tourism is definite, especially in the requirements of cost and quantity. The customers for space tourism do not need to stick to usage of hydrogen produced from non-carbon materials for clean energy. The space vehicle operators deployed on a global base. This will be a good opportunity for liquid hydrogen industry to consider global supply network. Once technology has been established for large scale use of hydrogen, the space tourism will also contribute to development of clean energy hydrogen material, such as application of dedicated hydroelectric power stations for electrolytic production of hydrogen.

8. Conclusion

Liquid hydrogen is the key issue for space transportation to be used for space tourism. Considering the early phase operation of public space transportation and the present technology of liquid hydrogen production and transportation, space tourism featured by low price and mass transportation will be technically feasible. The future of liquid hydrogen business will be opened by this customers and will be followed by new energy for mankind.

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6. This figure was based on a concept developed for Committee for SPS Study, March 1994

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