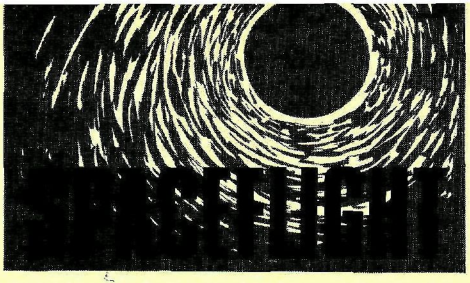


By DAVID BAKER

Economics of the Space Shuttle

The Shuttle was hailed as a major technical step forward when it appeared on the scene five years ago, sponsored by a Nasa anxious to keep the huge Apollo industrial machine in being. The Shuttle will undoubtedly have a major part to play in the American and European space programme being schemed for the 1980s, but is not perhaps the total launch vehicle that Nasa appears to consider it. If you have a 65,000lb manned scientific laboratory to place in low Earth orbit, then the Shuttle is just the job. But if you have a 1,000lb communications satellite bound for stationary orbit (and paid for by the shareholders) a good old-fashioned rocket will do the job at half the cost.

NOW THAT THE SPACE SHUTTLE is well under way the technical barriers are coming down and confidence is backed with an enthusiastic optimism for the golden age of cheap commuter travel between Earth and near-space. Just three years ago the much publicised Space Station, a follow-on to Skylab, began to price itself out of future plans and the container method came in. By packaging several instruments together and mounting them on a pallet, the Shuttle's own cargo bay will serve as the platform from which scientific tasks may be conducted, so capitalising on the enormous ready-made volume built in to the Orbiter. If men are needed to tend the equipment a cheap, pressurised compartment can be carried alongside. This, in essence, is Spacelab, and flights using this European-built laboratory will be called Sortie Missions.

But the Shuttle is not an end in itself and even with Spacelab in the cargo bay it will realise only a small part of the ambitious programme now envisaged for it. To effectively plan a space programme for the 1980s Nasa has built up a Mission Model, using proposals for the use of satellites or spacecraft as a yardstick from which the payload priorities over the next decade and beyond can be determined. An earlier plan developed in 1971 foresaw 327 possible payloads in a 12-year period and the present model raises this to 507 as a result of cancellation of the Space Station. This is naturally more cost-effective because of the increased launch rate. Non-Nasa Government agencies, private consortia and possible European payloads add a further 175, while the Department of Defence estimates that it will require 304 payloads to be flown into orbit.

Two types of mission

Because the Shuttle will be capable of carrying more than one payload per flight the 986 packages can be condensed into 725 flights in the 12-year period between 1980 and 1991. Of this total Nasa will launch 501, or 69 per cent. The Mission Model is best analysed by dividing it into Sortie (Spacelab) flights and direct-launch missions, in which a satellite is put into orbit or retrieved. About 34 per cent of all Shuttle flights will use Spacelab, and less than half of these are expected to use the unmanned pallet alone (i.e. without the habitable pressure module). Only 12 per cent of Spacelab flights are devoted to non-US payloads, while US commercial users account for 3 per cent and Nasa for 85 per cent. Thus 34 per cent of all Shuttle flights support 69 per cent of the payload envisaged. The remaining 31 per cent of Shuttle payloads will be direct-launch satellites encompassing Earth-orbit, deep-space and planetary objectives.

But the Shuttle has limitations on performance and not all the anticipated payloads can be launched by the Orbiter alone, although some flexibility exists for tailoring the Shuttle to specific payloads. Normally the Orbiter will carry 23,880lb of propellant, sufficient to provide a 1,000ft/sec velocity change for manœuvring purposes from the two 6,000lb-thrust engines mounted in the rear fuselage. These rocket motors will be used to provide the final boost into parking orbit, to circularise the orbit at a desired altitude, to provide the energy needed for all orbital changes, and to de-orbit the craft at the end of the mission. Flights from the Kennedy Space Centre, from due east up to 55° inclination require less than 150ft/sec velocity change to reach a 50 x 100 n.m. orbit, while a launch from Vandenberg AFB, 55° 104° inclination, needs 350ft/sec to reach the same orbit after main-engine cut-off. This allows the big propellant tank to fall back to the atmosphere without the need for a retro-rocket. Polar flights are heavily penalised by the increased velocity demand, and these are reflected in the payload figures.

Payloads and orbits

In basic form the Shuttle will be capable of placing a 65,000lb payload in a circular 28·5° orbit at 210 n.m. altitude. With the same payload it can attain a 450 n.m. apogee from a 100-mile orbit. For a 90° orbit the payload is reduced to 35,000lb, the altitude falls to 200 n.m. and the maximum apogee available is only 390 n.m. These figures represent the best trade-off between altitude and payload, although weight changes have only a marginal impact on the orbit and the absolute altitude attainable is relatively insensitive to off-loading from the cargo bay. This is reflected in the payload figures for the 28·5° orbit; whereas 65,000lb can be carried to a circular 210 mile path, reducing the payload weight to 1,000lb raises the altitude by only 75 miles.

To reach higher orbits the Shuttle can be fitted with up to three supplementary fuel tanks fitted in the cargo bay and fed to the two manœuvring engines by means of additional plumbing. With all three tanks installed the Orbiter gains an extra 1,500ft/sec manœuvring capability over the 1,000ft/sec available by using the integral tanks. This permits the Orbiter to deliver 25,000lb to a circular, 585-mile orbit at 28·5° inclination, or a 1,040-mile apogee from a 100-mile perigee. But even this is too low for many of the payloads proposed in the current Mission Model, in which 43 per cent of all flights require a supplementary method of propulsion. In fact, 17 per cent of all Nasa and DoD missions involve synchronous orbits and this reflects a dilemma of the entire programme.

For several years the Shuttle was seen as a cheap economic launch vehicle, carrying scientists destined for large orbital laboratories and piloted by a cadre of astronauts, ferrying massive supply containers to the permanent Space Stations. The demise of the Space Station has given predicted launch rates a boost, as noted earlier, by transferring orbital laboratory experiments into the Shuttle itself. However the economics of Shuttle launch operations can no longer be regarded as a challenge to the existing family of expendable rockets. This is due both to relatively high launch costs compared with small rockets such as Scout and Delta, and in the higher percentage of flights needing orbital altitudes in excess of those attainable by the Shuttle. The extra propulsive stages needed for these flights cannot be regarded as payload, but must be chargeable to the Shuttle. To do so would be tantamount to classifying the Saturn V third stage as part of the

Saturn's payload. Because of this the launch cost per lb of payload weight increases well beyond the $160 obtained by dividing launch cost by maximum payload. In fact, several flights indicate a financial disadvantage in using the Shuttle.

An example of this reasoning is illustrated by the proposed 1986 Mariner-Uranus mission. Although the weight in the cargo bay exceeds 46,000lb the actual spacecraft weighs a mere 2,137lb. Two launch cost figures can be deduced from this. If the entire contents of the cargo bay are charged as payload the launch cost per pound of payload weight comes to $218. If, however, the Mariner spacecraft alone is deemed to be the payload then the launch cost is $4,560/lb payload.

This is an extreme example but it serves to show the influence of an additional propulsive stage in the Shuttle. The Mission Model referred to earlier indicates how effective the Shuttle can be if used for only those missions where a heavy payload is required. For example, Nasa forecasts 14 Shuttle flights into near-Earth orbit in 1980. The average load on each flight will be 25,072lb and since all of this is payload the launch cost comes out at a competitive $361/lb payload weight.

Economics less attractive

Taking another 12-month period, 1983 for example, Nasa expects to mount 40 flights and the picture here becomes very different. The Mission Model anticipates 27 direct Shuttle flights and 13 missions involving the use of an additional propulsion unit. The average payload weight per flight reduces to 13,909lb and the launch cost increases to $674/lb payload weight. Again, the additional propulsion unit needed reduces the cost advantage over expendable rockets and since a higher fraction of DoD payloads require such a boost the economics become less attractive.

Because the Shuttle can offer many advantages denied to the conventional launch vehicle, such as re-usability, retrieval of redundant or faulty satellites and the return of a propulsive stage incapable of Earth-entry by itself, any evaluation of economics must take into account the entire programme envisaged for the period 1980-1991. Based on the current Mission Model, accommodating 986 payloads on 725 Nasa/DoD flights, the Shuttle programme would cost $49,370 million at 1972 prices. Included in this estimate is the need for 80 expendable rockets of the Scout, Delta and Titan classes during the 1980-1982 build-up period. Seven Shuttle vehicles are required to support this Mission Model and the three-year build-up envisages maximum acquisition rates of follow-on Orbiters, so keeping production costs down.

Gross benefit

By comparison, the equivalent traffic rate using conventional rockets would cost $63,470 million. The difference between Shuttle and expendable models' shows a gross benefit of $14,100 million during the 12-year period. However, it should be stressed that the expendable rocket model uses criteria developed for the Shuttle, with payloads optimised around the Orbiter. By designing the payload model for expendable rockets in the first place the Shuttle would be hard put to justify its existence. Clearly the new Mission Model is built around the Shuttle itself and this further enhances the argument that not only is Nasa developing a new launch vehicle but also promoting a re-direction of effort in the entire space programme.

As the annual launch rate is reduced, so the economics become increasingly unfavourable to the Shuttle. It is instructive to compare the projected launch weights in the Mission Model with those of the past 12 years. The highest annual Nasa total was that of 1972 when 33,645lb was launched, but the average over the last 12 years has been only 14,058lb per annum. This excludes manned flights since a true comparison must ignore the abnormally heavy weights associated with these programmes of the past. There is no equivalent in current planning for the Gemini/Apollo/Skylab projects and such figures would serve only to cloud the issue. Seen against this past 12-year record are the predicted launch weights for the future and in three typical years taken from the 1980-1991 Mission Model the comparison sets a different pace. Some 351,000lb is to be launched in 1980, 556,356lb in 1983 and 1,052,525lb in 1990. It is this level of effort which generates the $14,100 million cost benefit mentioned above. (DoD missions are excluded from both sets of figures.) It remains to be seen if Nasa, in concert with other users such as the European Space Agency and Intelsat, can really generate such a busy payload traffic from a relatively static budget.

As we saw earlier Nasa and the DoD will not be able to fulfil all their needs with the present Shuttle performance, even with additional fuel for the two manœuvring engines. Because of this the USAF is to adapt an existing rocket stage for use with Shuttle payloads from 1980. The Interim Upper Stage, as it is called, will be an expendable booster and will probably take the form of a modified Agena. By 1984 it will be replaced by the Tug (to be developed by Nasa), a more sophisticated propulsion unit capable of dispatching satellites to synchronous or high-altitude orbits, boosting spacecraft to the planets and bringing back payloads to the Shuttle for return to Earth. The interim vehicle and the Tug will both be made available to customers needing them.

It is too early yet to discuss the design aspects of either the Interim Upper Stage or the Tug—manufacturers are only just starting to look seriously at the concept—but the performance requirements are already defined and this indicates, in turn, the ultimate potential of the first-generation Shuttle.

The specification for the cryogenic Tug requires transfer of a 7,000lb payload to synchronous orbit and the return of the vehicle to a 160 n.m. parking orbit. It is then retrieved by the Shuttle, placed in the cargo bay and returned to Earth. If the Tug is on a satellite retrieval mission the down-load is limited to 4,250lb, or 2,750lb on a combined deploy/retrieval flight.

The details

To accommodate these requirements the Tug would be about 35ft long, 15ft in diameter, with a dry weight of 5,200lb and a maximum propellant weight of 55,700lb. The performance calls for a 15,000lb-thrust engine with a specific impulse of 461sec. However, the Tug will not be available before 1984 and the less powerful Interim Upper Stage will not make available anything near this performance during the first five years of Shuttle operations. Even the Tug will not provide the performance needed to meet the requirements for several of the proposed planetary missions. For instance, the velocity increment of 18,000ft/sec needed to reach the outer planets would demand the use of a kick-stage attached to the payload itself. The Tug would propel the spacecraft to a partial escape trajectory, separate and then return to the Shuttle's 160 n.m. orbit. The payload meanwhile would need an additional 6,000ft/sec from the expendable kick-stage to escape from the Earth's gravitational influence. This compromises the economics even more owing to the loss of the supplementary boost stage, which disappears into space along with its payload.

It is too early to be dogmatic about projected mission models for the 1980s. The existing model, developed by Nasa and the USAF, assumes a static Nasa budget of $3,300 million at 1972 prices but it is difficult to see how the high launch rate can be sustained. For the Nasa flights alone (501 from 1980 to 1991) the Mission Model calls for an average annual outlay of $390 million in launch costs alone. This assumes each Shuttle flight will cost $9·05 million at 1972 prices, with an extra $1 million for each of the 152 Tug flights.

Nasa has consistently attempted to justify the economics of a Shuttle-based space programme on the $5,500 million development figure. But this covers only two Orbiters, and the Mission Model now proposed requires procurement of five more Shuttles at an estimated $250 million each. In addition to this the payload prediction includes 12 Interim Upper Stages, seven Tugs and 16 kick-stages. Development of the Tug alone could cost $1,000 million, excluding additional models. Finally, planning for the

SPACEFLIGHT

Spacelab element envisages five support modules (i.e. the pressurised, manned laboratories) eight experiment modules (cylindrical containers attached to the rear of the support modules, carrying experiments) and 45 separate experiment pallets. In short, a lot of equipment will be needed to support the 986 payloads proposed and it is difficult to accurately predict the effects on the economics of even a minor slip in development schedules.

Assuming that the ambitious programme anticipated for the 1980s is a realistic proposition the $14,100 million cost advantage in using the Shuttle for 12 years is going to be offset by the increasing quantity of equipment necessary to support such a venture. Any delay in introducing the full inventory of Shuttles, Tugs, kick-stages and other vehicles now envisaged would keep expendable launch vehicles in business for years. Commercial users such as Intelsat will undoubtedly press vigorously for the retention of conventional rockets, particularly Scout and Delta, unless means can be found to substantially reduce the nearly 2:1 cost penalty of using the Shuttle.

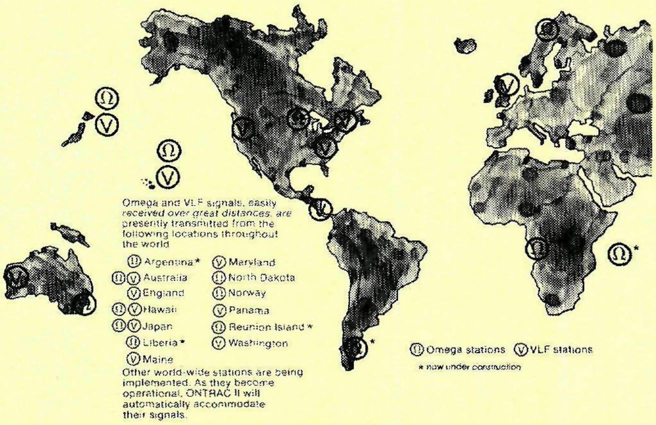
But if these figures reveal anything at all it is that the Shuttle must be seen as an investment in future space capability, bearing in mind the limitations imposed by the phased introduction of equipment. The Mission Model assumes availability of an interim Tug in 1981, capable of re-rendezvous with the Shuttle but not of retrieving a satellite from high altitude. Now that the USAF has pursued the Interim Upper Stage as an expendable unit Nasa will be unable to retrieve satellites above 350 miles until the Tug appears in 1984. Combined deploy/retrieval flights lower this figure considerably. Also, the 12 Interim Upper Stages demanded by the Mission Model assume them to be recoverable. By throwing each unit away for the first five years of Shuttle operations the economics are further compromised.

Clearly, the launch of 800,000lb payload per annum relies on too many factors converging at the right time. The ambitious Mission Model has too many parallels with the programme proposed in 1969 which envisaged long-duration stations in space, lunar bases, lunar orbit stations and nuclear shuttles, to be wholly relevant today. Nasa has to develop and effectively use the Shuttle to survive another decade of space operations, but an over-optimistic attitude has, in the past, left the agency with a string of cancelled projects. Only a realistic attitude to future requirements can hope to reverse this trend.

Franco-Indonesian agreement Under the terms of an agreement between CNES and LADAN (the Indonesian National Space and Aeronautical Institute) France and Indonesia are to undertake a five-year programme of space co-operation.

Avionics No 191

Ontrac II



APART FROM systems using satellites, airborne navigation equipment can be divided into three major categories: inertial, Doppler and radio. Each has several advantages and disadvantages when considered for a particular application. In many instances, radio navigation systems, which include Loran, Loran C, Decca, Omega and VLF, offer the best combination of cost, accuracy and reliability.

Although these radio systems have fundamental differences, each can be classified as either hyperbolic or rho-rho. Hyperbolic navigation utilises the difference in the distances to two transmitting stations obtained by measuring the phase difference between the signals from two stations. The result is to form hyperbolic lines of constant phase with the transmitting stations as the focus. The system's main advantage is that the receiving vehicle needs no on-board frequency standard. The major disadvantages are that two pairs of stations are required to give a unique fix and accuracy depends on the relative positions of the transmitting stations.

Rho-rho navigation utilises the distance to two stations. Distance, or change in distance, is obtained by measuring the phase difference between the transmitted signal and an on-board frequency standard. The resultant co-ordinate system consists of circular lines of constant phase with the transmitting station at the centre of the circle. Remembering that an on-board frequency standard is needed, rho-rho's two main advantages are that only two stations are required and that the area within which navigation information remains accurate is much larger than for hyperbolic systems using the same stations.

The US company Communications Components claims that its rho-rho system, Ontrac II, which uses Omega and VLF transmitting stations (see diagram), is among the cheapest, lightest, smallest and most cost-effective long-range navigation system now available. The company says that Ontrac's features compare favourably with (and in certain areas exceed) those of inertial systems. In the United Kingdom, Ontrac is marketed by FieldTech.

Ontrac II is built up from six components: receiver/computer, atomic frequency standard, station indicator, control head, display and emergency battery pack. When the broadband pre-amplifier and antenna are taken into account the total weight is only some 38·8lb.

Ontrac has four basic functions: en route navigation, terminal-area navigation and landing zone acquisition, position fixing and ground-speed indication.

The solid-state computer, which has the capacity to store and display information on the point or origin, up to five waypoints and the destination, converts time difference information into latitude and longitude. Using the control head, the crew can call up the latitude and longitude of the origin, present position, waypoints or destination together with heading, distance, speed and time to destination (or next waypoint) and whether the present position is left or right of track. A.N.H.