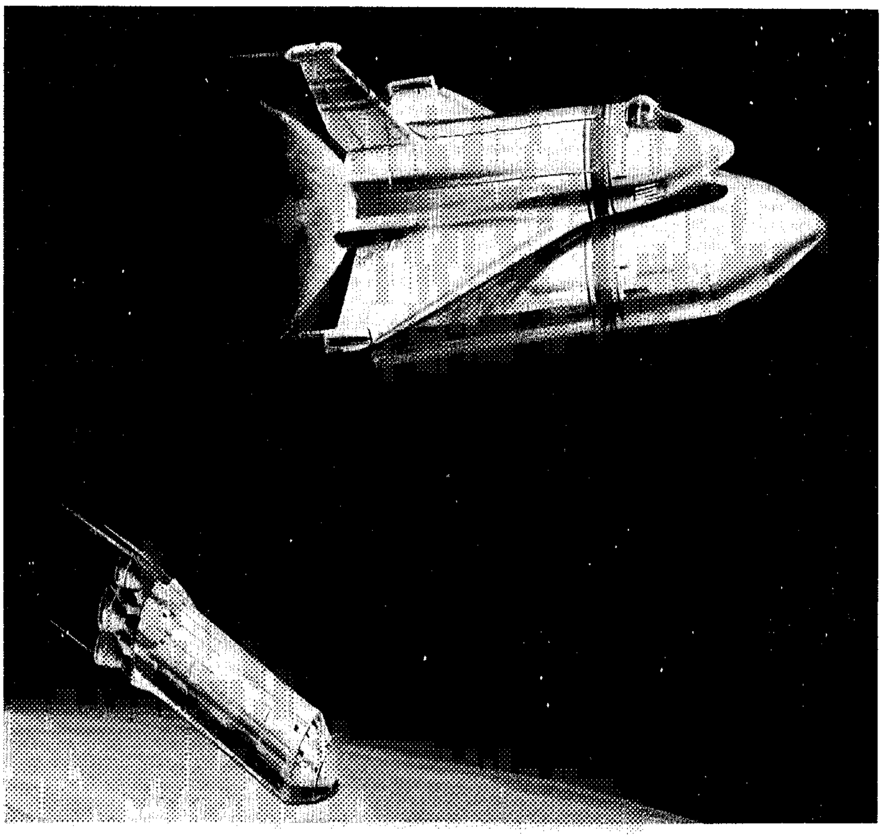
SHUTTLE SYSTEMS EVALUATION AND SELECTION



Volume I

EXECUTIVE SUMMARY

December 15, 1971

CONTRACT NAS 9-11160
MODIFICATION NO. 10S
B35-43 RP-30

GRUMMAN
BOEING

MSC-03822
VOL I

SHUTTLE SYSTEMS EVALUATION AND SELECTION

MID-TERM BRIEFING

DECEMBER 15, 1971

Volume I – EXECUTIVE SUMMARY

CONTRACT: NAS 9-11160, MOD 10S
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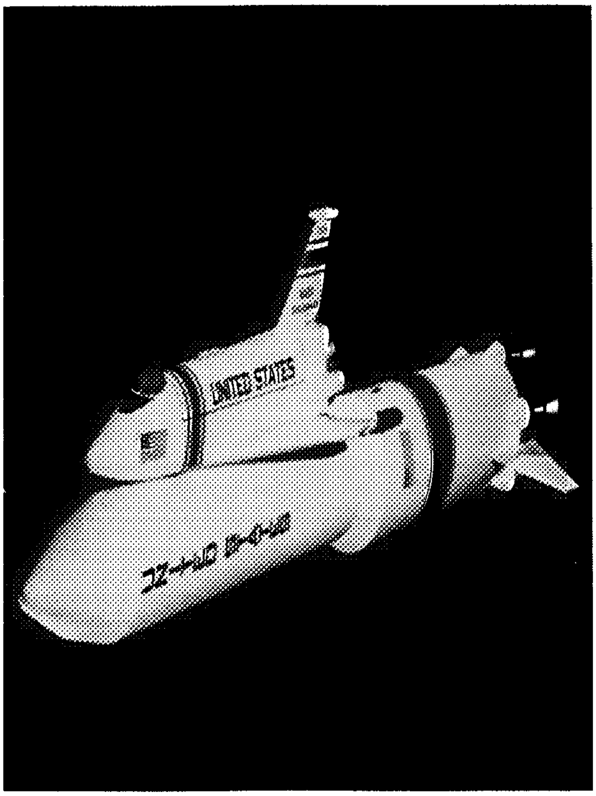
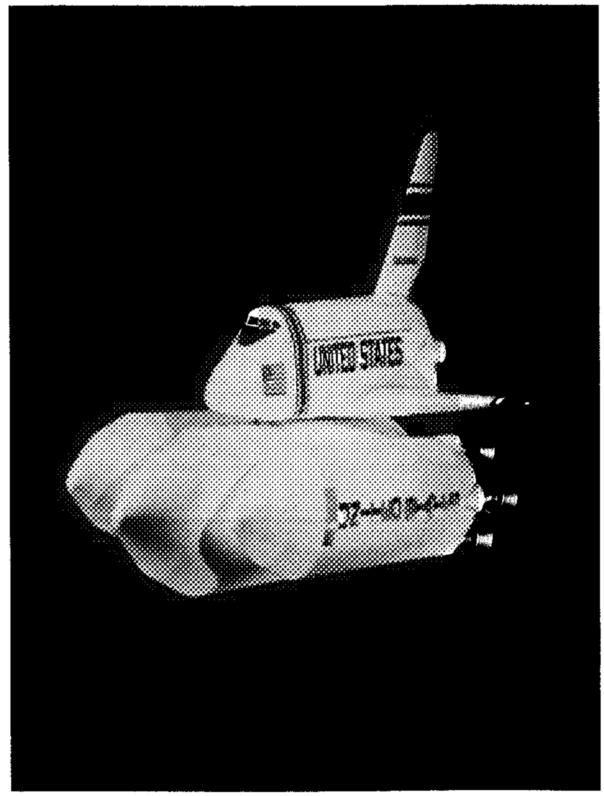
FOREWORD

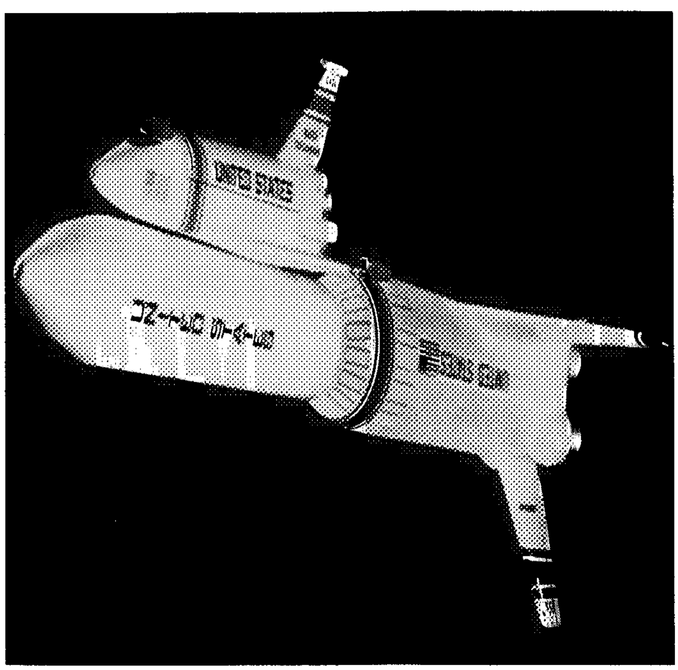
This is Volume I of five volumes which present the results of the first half of the second Shuttle Contract Extension Study. This volume contains a concise summary of the study results and conclusions.





BALLISTIC RECOVERABLE

RAO



FLYBACK

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GRUMMAN	• Systems Manager • Orbiter
BOEING	• Booster • Operations
AEROJET GENERAL TIRE GENERAL	• Cryogenic Tankage
AVCO	• Thermal Protection Systems
AVIONS MARCEL DASSAULT	• Thermal Protection Systems • Insulation Systems
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EASTERN	• Operations • Maintenance
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CONTENTS

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INTRODUCTION AND SUMMARY

This report is submitted to aid in the critical shuttle system selection of December 15th, and as part of our continuing effort to define low-cost shuttle systems. Our objective during the time period covered by this report was to penetrate the major issues affecting the selection of a space shuttle system from the contending options under study:

- The HO orbiter/ballistic recoverable booster series-burn configuration
- The HO orbiter/ballistic recoverable booster parallel-burn (rocket-assisted orbiter – RAO) configuration
- The HO orbiter/flyback LOX/RP booster configuration

The booster studies continued to emphasize the series-burn ballistic design, but the differences required for RAO application were identified and evaluated. In our systems studies, however, a major part of the activity involved definition of the RAO configuration parameters and technical problem areas, establishing approaches to possible solutions, and developing program costs.

In assessing the relative merits of the candidate configurations, we employed a three-step process:

- Based on cost, we narrowed the field to the ballistic booster configurations
- Using cost and technical risk factors, we evaluated the series-burn vs the RAO configurations of the ballistic booster system
- Finally, we assessed the potential of replacing the ballistic boosters with solid rockets

Our general approach in the configuration comparison process was to evaluate equivalent systems relative to each of the major decision points required so that each issue could be resolved on its own merits. For example, we treated the parallel- vs series-burn question on an equivalent orbiter engine basis and separately evaluated the phased-engine (J-2S/SSME) vs SSME (space shuttle main engine) engine- only issue.

The screening and selection process described above is illustrated in Figure 1.

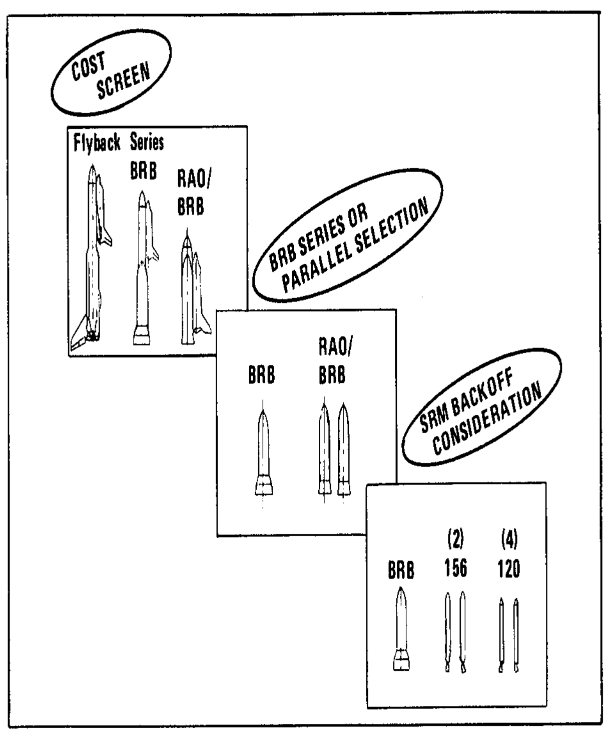

Fig. 1 Configuration Selection Process

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The conclusions of our studies to date are summarized as follows:

- The early program costs (DDT&E and peak annual funding – PAF) for the flyback system are higher than those of the other systems considered. (See Figure 2.) Furthermore, the cost risks of the flyback configuration would occur early in the development program. Since minimization of cost and risk during the early years of the program is considered to be of paramount importance, we eliminated the flyback system from further consideration in the selection process

- In comparing the ballistic booster systems, we considered a number of technical risk factors in addition to early program costs. The cost comparison, the risk factors considered, and our system assessment relative to these factors are shown in Figure 3. We concluded that system costs are not likely to be a major discriminator but that the RAO technical risks in the areas of controllability and booster separation are greater, and its sensitivity of payload loss to inert weight increase higher than for the series-burn system. We considered these factors to more than offset the lower risk of a smaller booster development and the somewhat more favorable solid-rocket motor (SRM) backoff potential of the RAO system. On balance, we feel that the technical risks are lower for the series-burn configuration. If, however, a solid-rocket-booster configuration is imposed by fiscal constraints, the RAO configuration lends itself to a somewhat lower-cost-per-flight implementation.

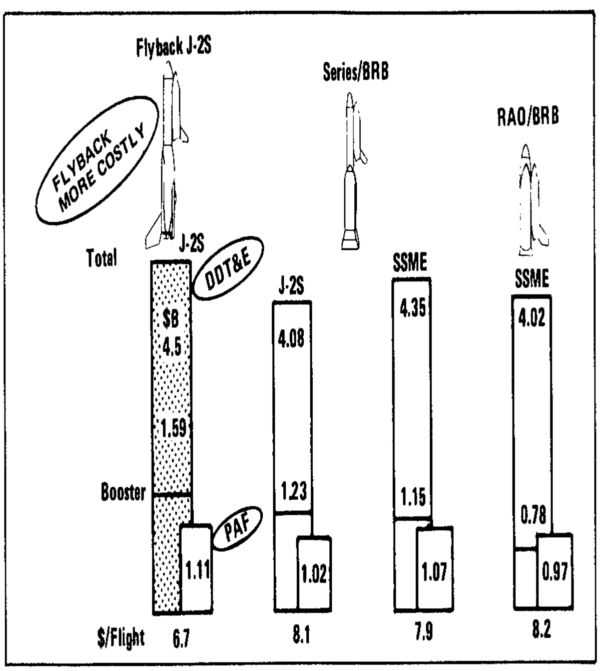
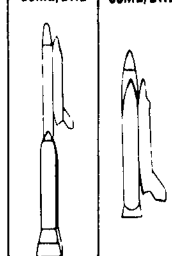


Fig. 2 Cost Comparison



	Series SSME/BRB	RAO SSME/BRB	
Lower DDT&E, $B	√ 4.35	√ 4.02 + Bstr TVC	STANDOFF
Requires TVC	√ –	√ –	
Better Abort Capability (No Alt Ldg Site Reqd)	√ –	√ –	
More Practical/Lower Cost SRM, $M/Flight	☐ 20	√ 17	FAVORS RAO
Lower Booster Inert Weight, K Lb	☐ 1080	√ 2 x 370	
Simpler Booster Separation	√ 1	☐ 2	
Cleaner Orbiter/Booster Interface	√ –	☐ –	
Lower Payload Sensitivity, Lb/%	√ 3183	☐ 3380	
Lower Cost of Payload Assurance, $/% Wt Increase	√ 13	☐ 25	FAVORS SERIES
Light Orbiter (Inert Wt), K Lb	√ 155	☐ 167	

Fig. 3 Evaluation Summary

Insofar as the choice between a phased-engine (J-2S/SSME) or SSME-only approach is concerned, initial use of the J-2S engine results in a larger (approximately 1M lb GLOW) but less costly (approximately $270M DDT&E) configuration than the SSME version. On that basis, we recommend its consideration. However, if an SSME-only approach is desired, we recommend the use of approximately 1.2M lb installed thrust in either a three- or four-engine arrangement. This minimizes SSME development cost.

STUDY OBJECTIVES

At the conclusion of the previous four-month study extension, we reported on the configuration, technical, and cost issues of the series-burn/ballistic booster and flyback booster systems. We concluded that the HO tank orbiter should be baselined and that phased development of the orbiter offers significant cost savings during the early program phases. All subsequent studies thus baselined the external HO tank/orbiter and assumed phased development of avionics and TPS. The issue of engine phasing, however, remained open, and one of the objectives of the second contract extension study was the resolution of that question. The major study objectives are summarized in Figure 4. Primarily, we were concerned with developing sufficient technical and cost data to allow a comparison and evaluation of the configurations and systems shown in Figure 5. The major study emphasis was placed on the booster aspects of the systems shown, since the orbiter/tank combinations are essentially invariant (except for tank size) across the configurations studied. The report on booster design status thus becomes a major ingredient of this report.

In addition to the primary configurations studied during the past six weeks, we also looked at the possibilities of developing a solid-rocket backoff for the ballistic booster and the evaluation of such a backoff potential also became an objective of this study.

- Compare & Evaluate Flyback, Series-BRB, & RAO Shuttle Systems
- Recommend Most Practical in Light of Technical Funding Limitations
- Report BRB Detail Design Data
- Identify SRM Backup Capability for BRB
- Show Performance/Cost Differences for J-2S/SSME vs SSME Only
- Report Swing-Engine Status

Fig. 4 Objectives

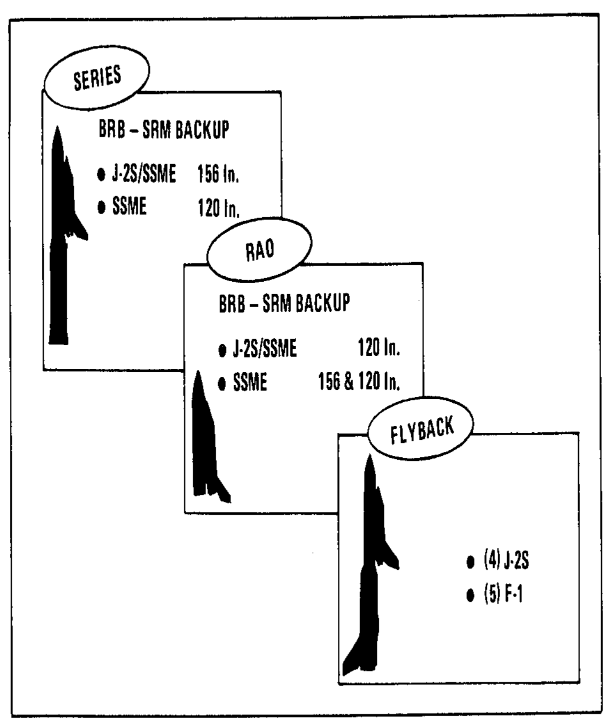


Fig. 5 Configurations

Selection of the point designs for the SSME and J-2S/SSME versions of the series-burn configurations was based on the performance and cost trending data shown in Figures 6, 7, and 8.

Selection of the SSME version (which has the new high-pressure space shuttle engine on both the Mk I and II orbiter) of the series-burn configuration was based on the data of the left-hand curves of Figures 6 and 7. Both GLOW and program cost decrease as orbiter engine thrust increases, but the rates at which they decrease appear to level out beyond the 1400K-lb total thrust value. We thus selected 1500K lb as the orbiter thrust. We chose as the point design a staging velocity of 5000 fps, which is somewhat higher than the staging velocity yielding minimum GLOW and cost. This choice resulted in a reasonably sized HO tank and acceded to NASA's desire to keep staging velocities in the 5000- to 7000-fps range.

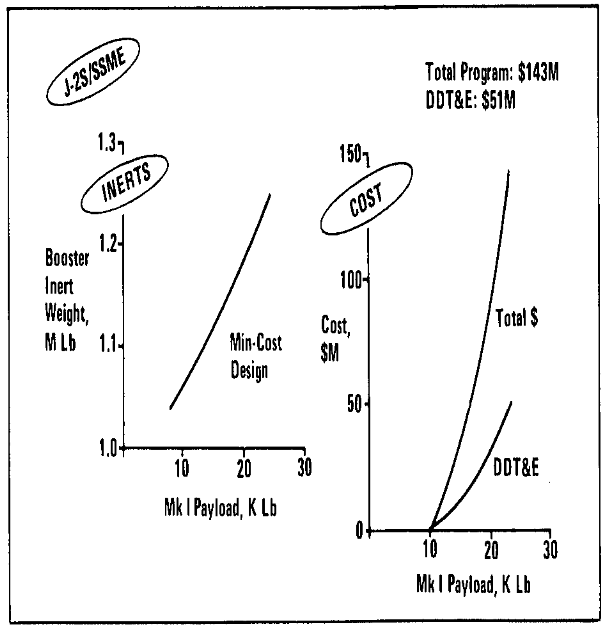


Fig. 7 Series BRB Cost of Max Mk I Payload

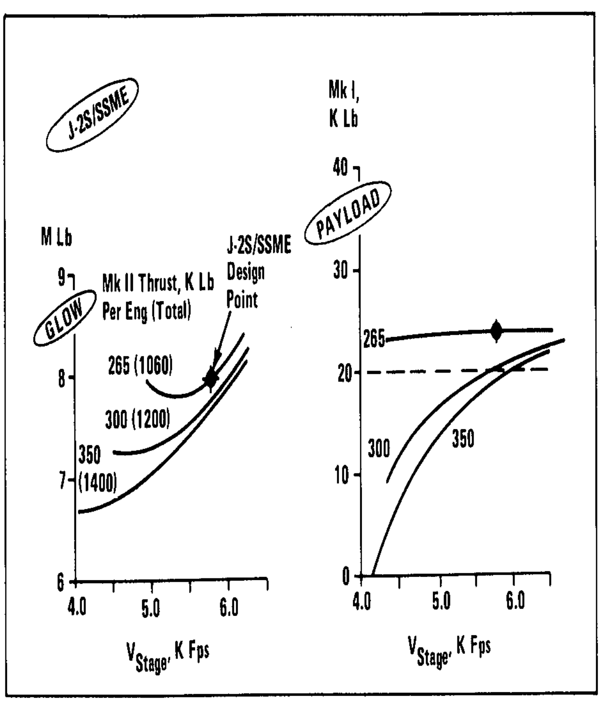


Fig. 6 Series BRB Performance

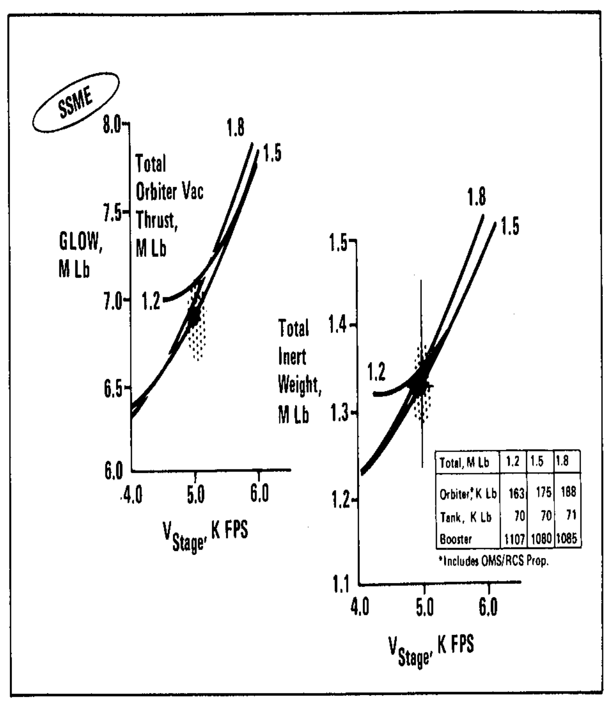


Fig. 8 Series BRB GLOW & Total Inerts

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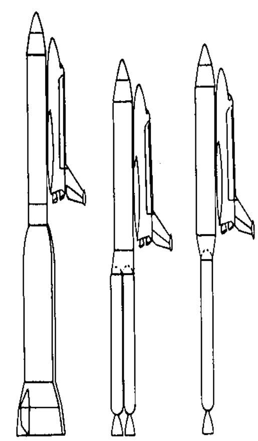
The selection of the design point for a configuration which includes changing the engine from a J-2S for Mk I to an SSME for the Mk II orbiter is somewhat complicated by the requirement to achieve a reasonable Mk I payload. Figure 6 shows the effect of SSME (Mk II) thrust selection on Mk I payload. It is clear that if 20,000 lb is a lower limit on Mk I payload, the Mk II SSME thrust level must be close to that of the J-2S engine (265K vac thrust per engine). Accordingly, we chose an SSME with a thrust level equal to that of the J-2S and selected a staging velocity of 5800 fps, which is a little higher than the staging velocity at the cost and GLOW buckets. Figure 7 illustrates the total program and DDT&E cost penalty associated with choice of SSME engine thrust level as a function of Mk I payload capability. A higher SSME thrust decreases Mk II system GLOW and overall development cost but also decreases Mk I payload. (See Figures 6 and 7.) The DDT&E cost penalty associated with our design point relative to a 10K-lb Mk I payload configuration is about $50M, or $3700 per lb of payload.

SRM BACKOFF

In our studies, we considered the potential backoff position to solid-rocket boosters in the event that either unforseen development problems on fiscal constraints required abandoning the ballistic booster.

Having selected the design points for ballistic boosters, we investigated single- and two-stage solid-rocket-motor boosters for the design point orbiter and tank weights. The results of these studies are summarized in Figure 9 in terms of major performance and cost parameters. In general, SRM backoff is feasible, with no particular advantage of two-stage over single-stage booster approaches. The GLOW of the SRM systems is generally lower than that of the ballistic booster systems, as are the costs. The cost comparison, however, is based on the assumption that the solid rockets are being developed as the primary boosters and not as a substitute for the ballistic booster sometime downstream in the program. Added costs would be incurred to implement the program change. The magnitude of these costs is a function of the timing of the program redirection.



	J-2S/SSME			SSME		
		156-In. SRM			SRM	
	BRB	1-Stage (3)	2-Stage (3)	BRB	156 1-Stage (3)	1207 2-Stage (6)
PERF, M Lb						
• GLOW	7.96	5.70	5.30	6.90	5.21	5.33
• BLOW	6.79	4.51	4.12	5.62	3.92	4.04
• Bstr Inert	1.26	0.573	0.513	1.08	.495	.539
COST						
• Mk I DDT&E, $B	4.08	3.16	3.21	4.351	3.51	3.48
• PAF, $B, '75	1.02	0.78	0.79	1.07	0.85	0.86
• Cost/Flt*, $M	8.11	21.97	20.51	7.89	20.4	22.5
• Tot. Prog, $B	10.83	14.49	13.92	10.40	13.67	14.54

*Not Amortized

Fig. 9 Series BRB/SRM Backup Cost/Performance

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ENGINE SELECTION

Figure 10 compares major characteristics of the SSME and J-2S/SSME version of the series-burn configurations. We recommend consideration of the J-2S/SSME approach because of the lower DDT&E costs and the lower development risk associated with the J-2S engine. The launch arrangement of this configuration is shown in Figure 11.

If the decision is made to pursue only the SSME development, we recommend a total thrust level of approximately 1.2M lb to keep engine DDT&E reasonably low.

Other results and conclusions of the series-burn studies are summarized in Figure 12.

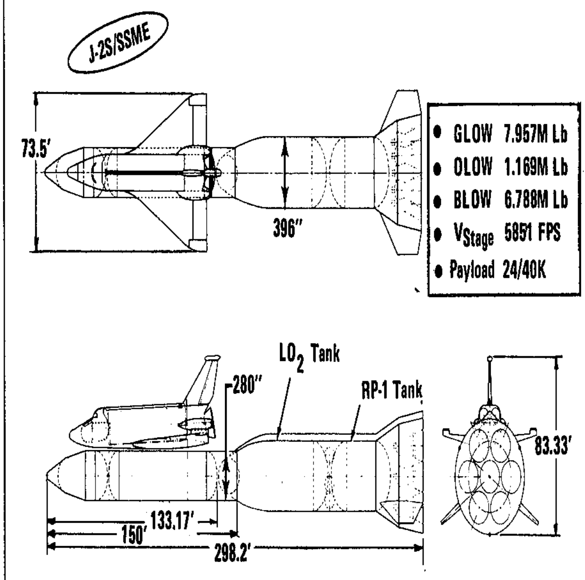

Fig. 11 Mk I Series Ballistic Launch Configuration

PERFORMANCE

	J-2S/SSME	SSME
	Mk I	1500K
• GLOW, M Lb	7.957	6.903
• OLOW, M Lb	1.169	1.287
• W_I Bstr, M Lb	1.262	1.081
• Orb Eng, No./T_V	4/265	4/375
• V_{Stage}, FPS	5851	5003
• Payload, I/II, K Lb	23.8/40	40

COST

	J-2S/SSME	SSME
• Mk I DDT&E, $B	4.08	4.35
• PAF, $B	1.02	1.07
• Cost/Flt, $M (Not Amortized)	8.11	7.89
• Tot. Prog, $B	10.83	10.40

Fig. 10 J-2S/SSME vs SSME Series Burn

- J-2S/SSME Requires SSME Thrust = J-2S (265K)
- Mk I Payload: 24K
- J-2S/SSME GLOW 1M Lb Higher Than SSME
- J-2S/SSME DDT&E Lower by $270M, PAF $50M
- SRM Backup Available for Both 3(156) but Cost/Flight of Backup Higher by 3 x BRB ($25M)
- Prefer J-2S/SSME Approach to Minimize DDT&E & Engine Risk

ON BALANCE

Fig. 12 Series BRB Summary

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The RAO system is characterized by the use of two booster modules on either side of the tank, rather than the tandem arrangement of the series-burn approach, and by the simultaneous firing of all booster and orbiter engines at launch.

In our sizing of RAO (parallel-burn) configurations, we used basically the same approach as discussed above for the series-burn case. The configurations studied are shown in Figure 13. For SRM backoff, we concentrated on 120-in. motors as being in a more mature stage of development than the larger-diameter solids.

Our studies were initially based on the assumption that attitude control during mated ascent burn would be performed by use of the orbiter engines and aero control surfaces only, since elimination of booster thrust vector control (TVC) was a very desirable objective. As we penetrated more deeply into the control problem, it became apparent that the use of booster TVC might become a requirement. Our sizing and cost data does not, however, reflect the use of TVC on the booster, although we will present estimates of the impact on both cost and performance if TVC (liquid-injection-type) is baselined for the boosters.

Whether booster TVC is required or not, the RAO configurations will generally benefit from greater orbiter control authority, since, even if the booster is designed for TVC, the liquid injection TVC system weight penalty is a function of the extent to which its utilization is required. Thus, in RAO sizing, we considered orbiter SSME thrust values in the range of 1.5-1.8M lb, as compared to 1.2-1.5M lb for the series case. The performance and cost trends for the all-SSME version of RAO are shown in Figure 14. The higher-engine-thrust orbiter results in lower GLOW but slightly higher program costs (primarily engine development costs). Because of the control consideration discussed above, however, we selected the higher-thrust orbiter engine system at a staging velocity (4751 fps) which is close to the 5000-fps lower limit desired by NASA and is almost at the cost bucket. The launch configuration at that design point is shown in Figure 15.

For the case of a J-2S/SSME Orbiter, the size trending data for that configuration is shown in Figure 16, which also includes the SSME orbiter data for comparison.

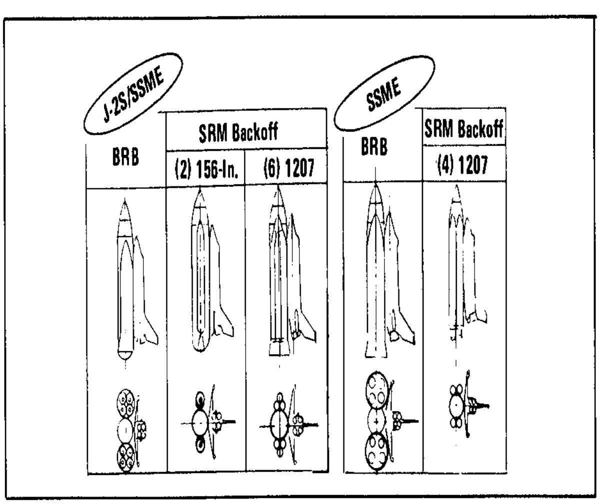

Fig. 13 RAO Primary & SRM Backoff Configurations

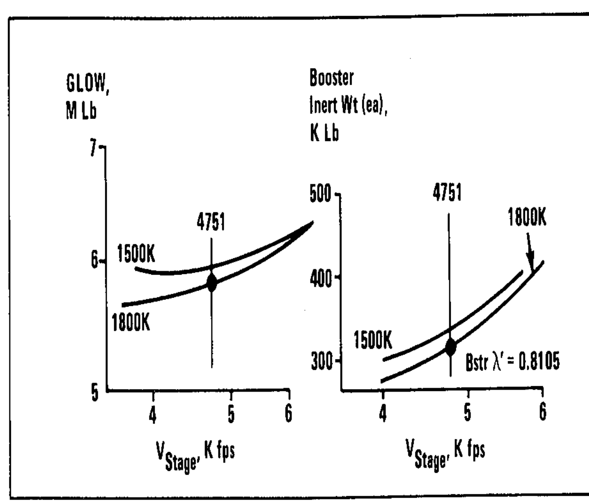

Fig. 14 RAO/BRB/SSME Sizing

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The selection of SSME thrust for the Mk II phase of the orbiter was arrived at in exactly the same manner as for the series burn case, i.e., we found that for any reasonable Mk I payload (20K lb or greater), the SSME thrust should be equal to the J-2S thrust (265K vac). Note in Figure 16 that the lower orbiter performance at the 4 x 265K lb (1.06 M lb T_{total}) thrust level makes the GLOW bucket move to higher staging velocities than for the SSME-all-the-way configuration. We selected a design point at 5900 fps, just to the left of the GLOW bucket.

The selection of backup solid-rocket motors was, as in the series-burn case, based on retaining the exact design-point orbiter and tank liftoff weight and sizing an SRM so that it would achieve orbit injection. The design points for the backup configurations are also shown in Figure 16. As expected, the SRMs, being more efficient boosters, tend to reduce overall configuration weight by about a million pounds.

The RAO launch configuration for a J-2S/SSME orbiter is shown in Figure 17.

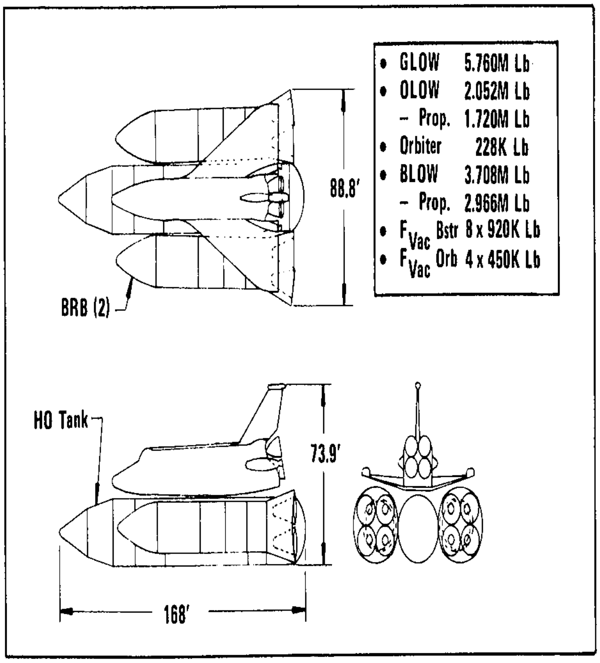


Fig. 15 RAO/BRB/SSME Arrangement

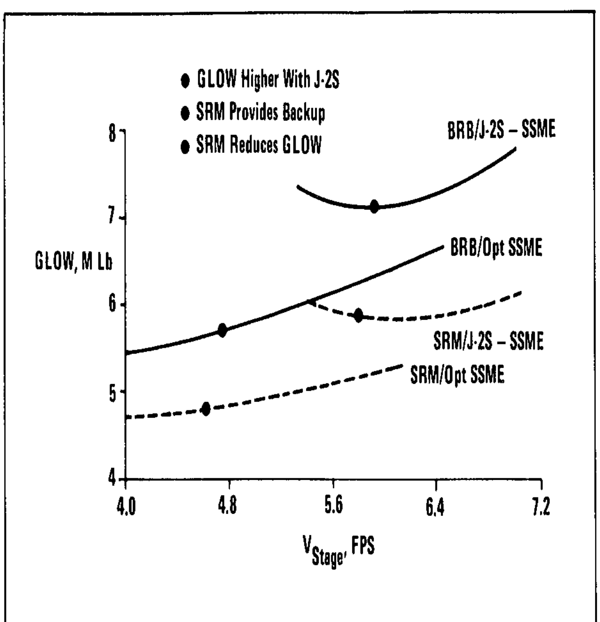
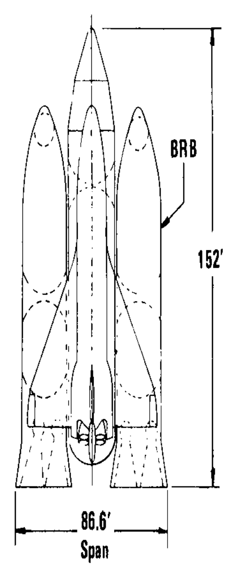


Fig. 16 RAO GLOW Comparison



Mk II Weights	BRB
GLOW, M Lb	6.957
OLOW, M Lb	1.647
Prop., M Lb	1.363
Orbiter	199.0
BLOW, M Lb	5.309
Prop., M Lb	4.332
F_{Vac} Bstr, K Lb	9.974
F_{Vac} Orb, K Lb	1.060

Fig. 17 RAO/BRB/J-2S/SSME Arrangement

The characteristics of the RAO concept generate two major problems – the controllability of the combined vehicle, and the requirement to jettison the two parallel boosters.

Controllability becomes a serious concern when considered in conjunction with the desire to minimize or eliminate booster TVC requirements. The fluid carried in the booster for liquid-injection thrust vectoring is used inefficiently, compared to propellants, and lowers the effecitve engine performance by an amount which is a function of the percentage of total mated flight time during which booster thrust vectoring is required. The TVC plumbing and valving also add inert weight to the booster, which is independent of percent utilization but is a function of the maximum thrust direction change required. It is, therefore, important to minimize both the duration as well as the extent of booster thrust vectoring for which the system must be designed, which, in turn, requires maximum available control authority from the orbiter. With this in mind, we selected a high total engine thrust (1.8M lb) and decided on a four-engine (450K lb each) configuration. The latter minimizes the effect of an orbiter engine failure, since the loss of one of four engines results in a smaller variation in both net thrust direction as well as magnitude than the failure of one of three engines. We also oriented the orbiter engines such that at gimbal angle null, the thrust vector sum of both booster and orbiter engines goes through the cg at max q. This leaves the maximum gimbal angle excursion available at the time dynamic control requirements are greatest.

Our control studies have concluded that there appears to be no requirement for booster TVC under normal or single-engine failure conditions provided that:

- In the event of a booster engine failure, the opposite engine is automatically shut down

- A vertical fin is placed on the underside of each booster, sized to lower the cp of the combined configuration from our present estimate of 18-20 ft above the cg to about 4-5 ft. This will reduce the magnitude of roll moments under max q conditions to within the control authority capability of the orbiter. (See Figure 18.)

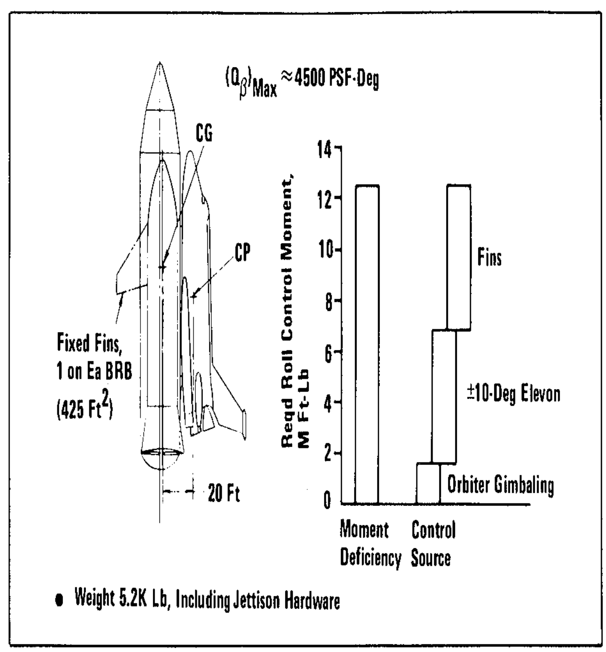


Fig. 18 Roll Control During Ascent

We concluded that engine-out conditions were critical for control, but that control margins are acceptable. More analysis and wind tunnel testing are required to confirm these conclusions. We decided to assume, at this time, that booster TVC is required and that in comparing RAO to the series-burn system, the absence of TVC will not be used as a configuration discriminator.

Booster separation also imposes difficult technical requirements, especially at high dynamic pressures such as might be experienced under abort conditions. We have examined various possible separation concepts (Figure 19) for both nominal and max q separation and have concluded that, although all can be made to work at normal staging (q = 60-100 psf), abort separation at high q imposes such high loads and aerodynamic effects that positive separation, using solid separation rockets on the booster, is the only feasible concept. We have sized separation rockets (two per booster) to provide about 200-in. separation distance between booster and tank at rocket burnout at max q. The separation rockets add approximately 9000 lb total system weight. The booster data presented herein do not, however, include this weight.

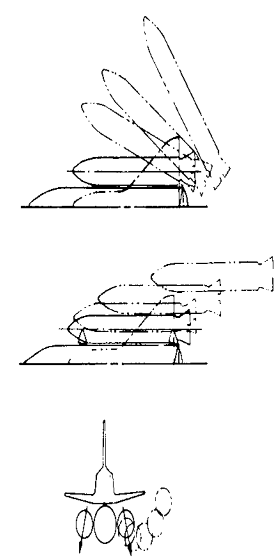


Fig. 19 RAO Booster Separation

RAO CONCLUSIONS AND CONFIGURATION COMPARISON

The technical conclusions of our RAO studies are summarized in Figure 20. The control and separation areas have already been discussed above. The issue of three vs four engines was also touched upon during the controllability discussion, where consideration of control authority with one-engine-out favored four engines. Abort considerations also tend to favor four engines because, again, the failure of one of four orbiter engines has less effect than one of three.

In comparing the J-2S/SSME RAO version to the SSME-all-the-way configuration, we considered weight, cost, and development risk. As shown in Figure 21, we see the same general effect that we observed in comparing the series-burn systems – weight increases but development cost decreases when the J-2S is introduced. In the case of RAO, we also introduced the additional consideration of SRM backoff potential. As shown in Figure 22, the SSME orbiter can be backed up by four 1207 SRMS, while the J-2S version of the orbiter requires six, thus considerably increasing the cost per flight of the backoff configuration. In our view, this additional factor of a more practical backup tends to reduce the development risk of the SSME-all-the-way approach to where, on balance, we recommend going that way on RAO.

- Control – Assume for Now TVC Required
- Separation More Complex – Needs Work
- 4 SSME (450K) Better Than J-2S/SSME Combination
- SRM Backoff Available: 2 x 156 In. or 4 x 1207

Fig. 20 RAO Summary

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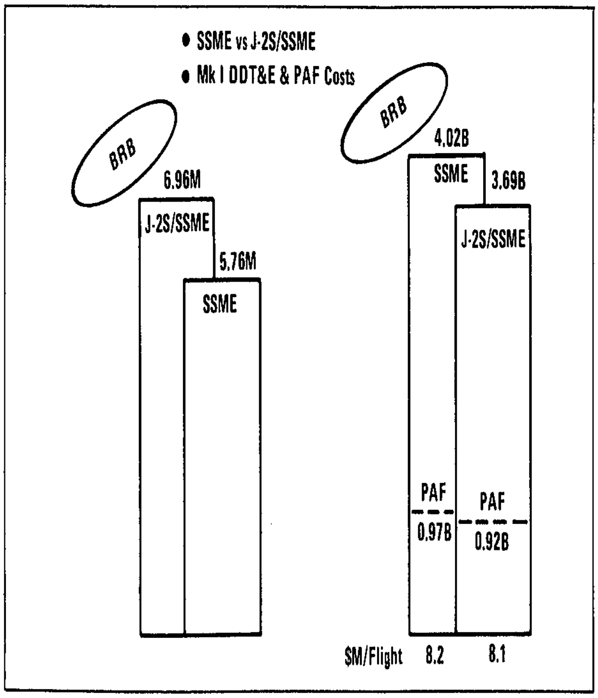
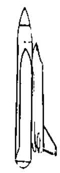


Fig. 21 RAO GLOW & Cost Comparison



PERFORMANCE	SSME			J-2S/SSME	
		Solid			Solid
	BRB	(2) 156	(4) 1207	BRB	(6) 1207
GLOW, M Lb	5.76	4.78	4.77	6.96	5.63
OLOW, M Lb	2.05	2.05	2.05	1.65	1.65
BLOW, M Lb	3.71	2.72	2.72	5.31	3.98
Orb Inert, K Lb	167	167	167	141	142
Bstr Inert, K Lb	742	347	359	977	539
Tank Inert, K Lb	103	103	103	85	85

Fig. 22 RAO/BRB/SRM Backoff

BOOSTER DESIGN STATUS

SUMMARY

The baseline ballistic recoverable booster (BRB) incorporates the simplicity of the pressure-fed engine with the inherent ruggedness of high-pressure tankage. Optimum staging velocities of between 5000 and 6000 fps are achievable for a recoverable pressure-fed booster, with water impact determining a significant portion of inert weight (12%).

A LOX/RP single stage series burn vehicle requires a booster lift-off weight of 6.56M lb to achieve 5500 fps V_{stage} and survive a 100-fps water impact with negligible damage. Development costs for the single-stage device are $1.27B.

A two-module LOX/RP pressure-fed booster for the parallel-burn retrievable orbiter configuration (RAO) stages at 4750 fps with booster liftoff weight per module of 1.8M lb. Development cost of this booster is $831M, which is 34% lower than for the series-burn booster because of lower inert weight.

STUDY CONFIGURATIONS

We have identified a variety of pressure-fed BRBs and SRM stages for both series- and parallel-burn with the orbiter. The series- and parallel-burn boosters have been matched to both Mk I (J-2S)/Mk II (SSME) engine orbiters and to optimum SSME orbiters. Booster staging

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velocities were selected based on a matched vehicle with minimum lift-off weight. Study configurations are identified and major characteristics shown in Figure 23.

SERIES-BURN BRB

Model 979-150A (Figure 24) is a recoverable single-stage pressure-fed booster utilizing LOX/RP-1 propellants with a tandem external tank hydrogen-oxygen (HO) orbiter that stages at 5500 fps. The booster stage uses seven identical rocket engines with a separage liquid-injection (freon) thrust vector control system. Individual oxidizer and fuel tanks are separated by an inter-tank structure in which some of the pressurization equipment is located. Aluminum alloy 2219 LOX tank and fuel tank operating pressures are 322 and 365 psia, respectively. Pressurization of propellant tanks is a dual system, using heated nitrogen in the LOX tank and hydrazine decomposition products in the fuel tank. These pressurants are also used in the reaction control system and as the hydraulic system power source.

The structure is predominantly aluminum semi-monocoque construction and features a water-impact keel and controllable stabilizer fins, which are required for high re-entry stability and trim. Structure is the dominant weight contributor. Tankage comprises 51% of this and is pressure-designed except for a portion of the nose which is designed by water impact. Heat sink and water impact loads primarily design the remaining structural components.

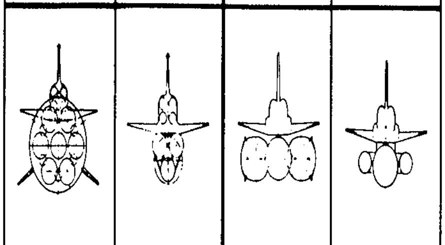
	Series J-2S/SSME		RAO/SSME	
	LOX-RP Baseline 979-150A	SRM Backoff 979-158A	Pressure-Fed 979-151	SRM Backoff 979-147
				
Vehicle				
OLOW, Lb	1,185,000	1,185,000	2,053,000	2,053,000
BLOW, Lb	6,568,300	4,350,000	3,708,000	2,753,000
V_{Stage}, FPS	5850	5800	4750	4520
Booster				
Length, Ft	160.7	126.0	137.7	133.0
Dry Wt, Lb	1,063,900		610,400	
Inert Wt, Lb	1,228,500	536,700	696,400	323,040
λ'	0.813	0.877	0.806	0.882
Propellant	LOX–RP	PBAN	LOX–RP	PBAN
Engines	(7) Press.-Fed	(3) 156 In. SRM	(4) Press-Fed/Mod	(2) 156 In. SRM
Thrust (SL), Lb	9,800,000	6,921,000	746,000	4,675,100
Booster				
DDT&E, $B	1.265	0.446	0.831	0.309
Total, $B	3.942	7.178	3.128	4.570

Fig. 23 Booster Study Configurations

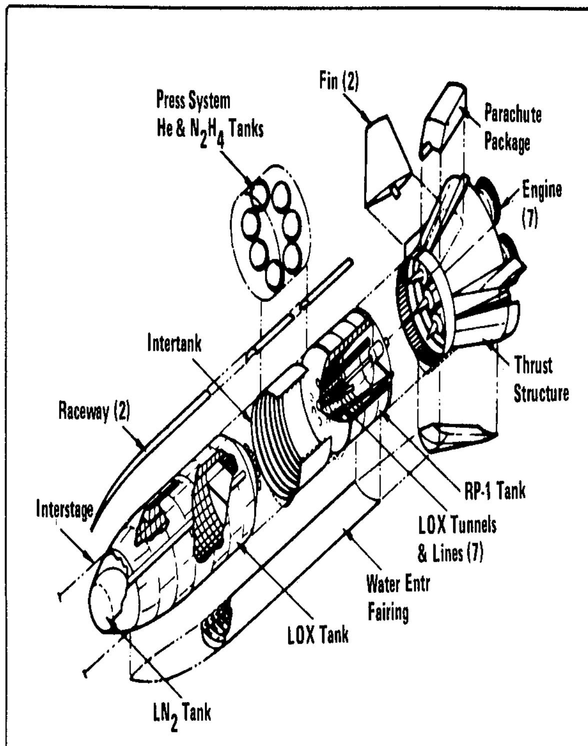


Fig. 24 RAO Baseline

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The ballistic recoverable booster phasing reflects a June 1, 1972 authority to proceed with an unmanned launch the end of September 1977 (64 months after ATP). The first manned orbiter launch is scheduled for March 1, 1978 (69 months from ATP) using the second production booster vehicle. The booster recovery system is installed on all booster vehicles, including the unmanned launch. Engineering releases are phased to support manufacturing buildup of the test articles and flight vehicles, starting with a subscale water-impact test article. The schedule is driven by the need to complete (1) testing of the development tanks prior to start of production-tank subassembly and (2) completion of clustered static firing tests prior to final assembly of the first flight vehicle. The configuration costs are driven by the combined environments of ascent/descent thermal heating and water impact that permits recovery. Designing the booster for these environments lowers operation costs from previous estimates by eliminating uncertainty as to structural damage.

PARALLEL-BURN BRB (RAO)

The parallel-burn booster, as shown in Figure 25, consists of two recoverable pressure-fed boosters utilizing LOX/RP-1 propellants attached to the side of an external-tank HO orbiter. The BRB module is 19.2 ft in diameter and 136.7 ft long.

The recoverable boosters use four identical engines, each with a thrust of 7.07K lb SL, for a total thrust at launch of 5.66M lb. An aft skirt is provided to protect the rocket engine installation and other booster subsystems from the high re-entry dynamic pressures and also from the high water-landing-impact loads. Two fixed fins are located on the aft skirt to provide the desired trim and stability margins during re-entry. Stage separation is accomplished at a burnout velocity of 4800 fps and an altitude of 140,000 ft.

CRITICAL ISSUES

The following booster design issues are critical in booster development. We have given these areas considerable study emphasis and plan to continue this emphasis to resolve them fully:

- *Ascent Control* – Liquid-injection TVC has limitations if large deflections are required, or small deflections for long durations. Further evaluation of the control requirements through flight simulations is continuing and alternate approaches, such as gimbaled engines, are being evaluated

- *Re-Entry Aerodynamic Control* – The current cg is too far aft for aerodynamic trim with a fixed fin. Two alternate solutions will be investigated:

  - Addition of a feedback flight control system that controls booster angle of attack by varying fin incidence, plus relocation of subsystems and addition of ballast, as required for stability and trim

  - Re-examination of re-entering at a high vs zero angle of attack using drag devices

- *Water Impact* – The loads and structural weight penalties must be minimized by reducing impact velocity as much as practical by recovery devices (parachutes and/or retrorockets), and by entering the water at angles which preclude rebound and minimize structural weight. Water impact tests will be required to establish proper design solutions

- *Recovery System* – Vehicle dynamics during parachute deployment must be established through subscale testing. In addition, significant advances must be made in parachute technology for manufacturing, packaging, deploying, and refurbishing the 192-ft diameter chutes

- *Propulsion System* – The pressure-fed BRB will require propulsion technology advances in the areas of high-thrust pressure-fed engines and feed-systems pressurization. These advancements will require early compatibility testing of corrosion-resistant materials coupled with subscale developmental testing to establish subsystem performance, durability, and operational-life capabilities

- *Materials and Weld Development* – The size, recovery, refurbishment, and systems requirements of the BRB require advancements in materials performance and fabrication technologies. In particular, further development of electron-beam welding techniques is required because existing gas-metal arc and gas-tungsten arc processes require excessive time for the heavy aluminum weldments planned

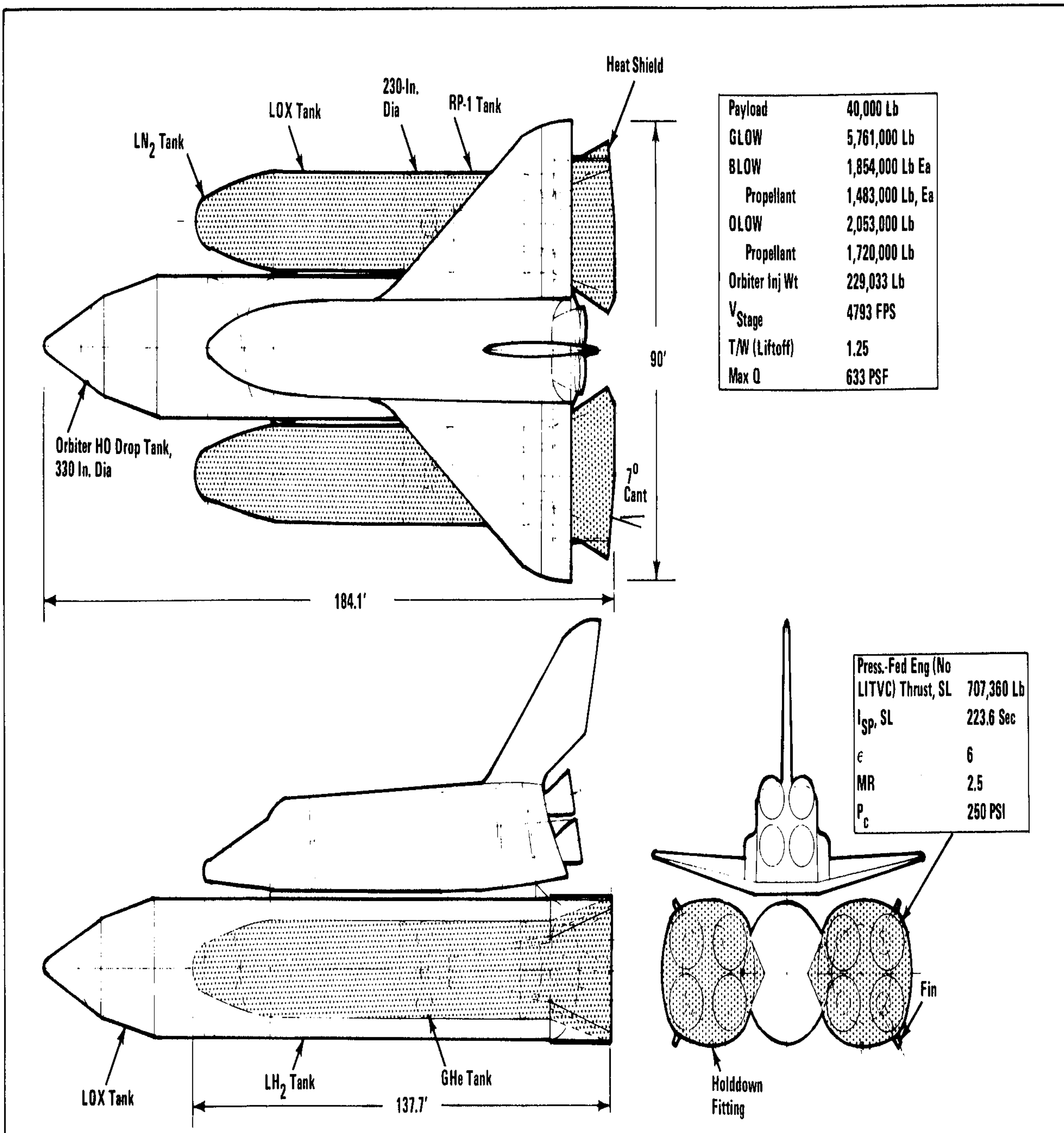

Fig. 25 Model 979-151 BRB

LOX/RP-1/RAO COST COMPARISON

The booster costs for the configurations studied are compared in Figure 26. The RAO concept using a parallel-burn BRB results in the lowest booster program cost. Its primary cost advantage accrues through its smaller size, yielding low production costs of the booster and lower engine and material costs. The series-burn LOX/RP-1 baseline program has an increased booster cost of 34% with an increased cost per flight of 18.8%.

FLYBACK BOOSTER STATUS

The primary issues addressed in the continuing studies of the LOX/RP flyback booster, Figure 27, were cost realism and configuration refinement. Cost estimation of DDT&E was improved through greater depth of analysis of the development activities required through FMOF. Operational cost studies were continued with further analysis of the operational timelines. In configuration development, greater confidence in the aerodynamic control capability was established through wind tunnel testing and piloted simulation studies. Further trade studies on external material selection resulted in a reduction of both costs and the number of different materials required. Although this solution increased the dry weight of the booster, we retained a payload margin over the 40K south polar requirement.

Program Funding and Scheduling

The funding required for DDT&E, production, and operations given below was developed from detailed manning and material estimates with key dates for the booster development master schedule shown in Figure 28. This curve represents the third iteration of the booster funding estimate. For all estimates, the total DDT&E cost has remained within 5%; however, peak funding has been reduced by $53M. This improvement in peak funding was made by decreasing the manufacturing and engineering overlap. The solid funding curve is based on a

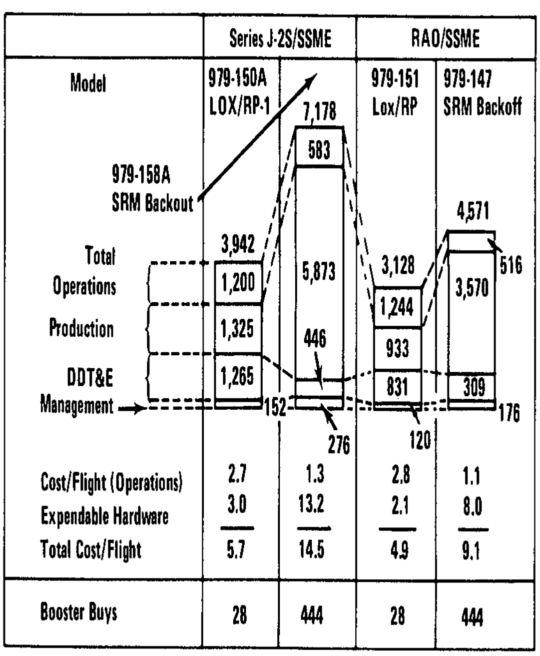

Fig. 26 Booster Cost Comparison ($M)

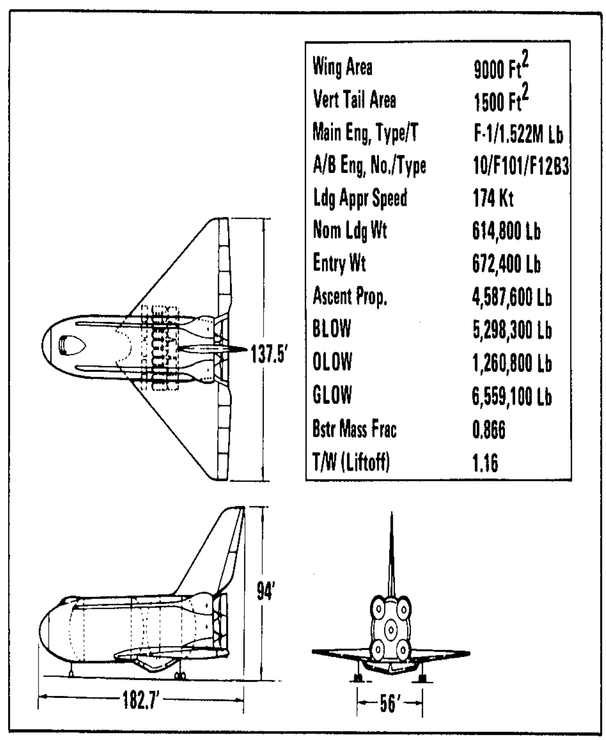

Fig. 27 Model 979-061A LOX/RP Flyback Configuration

June, 1977, FHF. This FHF date could be moved to the last quarter of 1976. However, any further movement to the left will increase schedule risk to an unacceptable level. Moving the FHF to December, 1976, increases peak funding by $19M.

Accommodation of Weight Growth

The configuration selected for the LOX/RP flyback booster is one which has an inherent capability to accommodate some significant changes in design requirements without causing redesign. Figure 29 illustrates the ability of the booster to accept increases in inert weight of either orbiter or booster. The payload of the baseline system – the F-1 (1522K) and J-2S – is approximately 54,000 lb, which exceeds the Mk II requirement by 14,000 lb. Other optional engine combinations (F-1A, uprated F-1, SSME) could provide additional accommodations for weight growth in excess of the existing 14,000-lb payload margin.

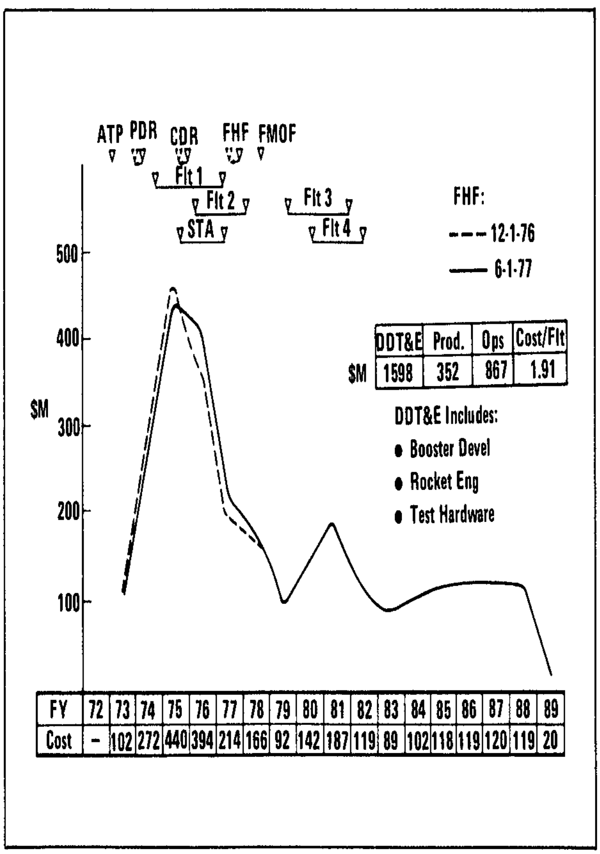

Fig. 28 LOX/RP Flyback Booster Program Cost

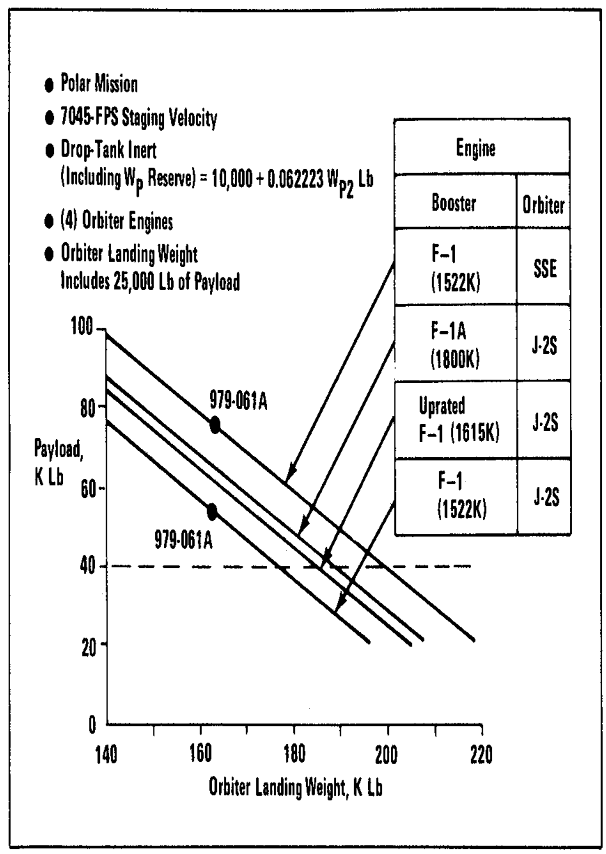

Fig. 29 LOX/RP Flyback Booster Accommodation of Weight Growth

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The systems evaluation process was carried out in three steps (see Figure 1):

- *Cost Screen* – We first compared costs of the three contending systems to see if any obvious conclusion would suggest itself.

  The costs we were concerned with are those affecting early program expenditure rates. We thus performed our evaluation on DDT&E costs and the resultant peak annual funding (PAF)

  required. The cost data comparison is shown in Figure 2 and is reproduced here for the reader's convenience as Figure 30. It can be seen that based on the above criteria, the flyback booster system is more costly than the other configurations

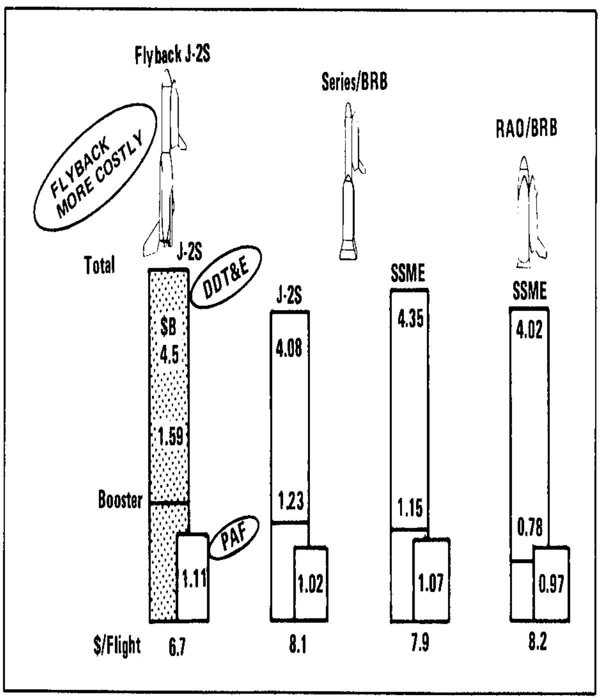

Fig. 30 Cost Comparison

evaluated, requiring nearly a half-billion dollars greater development funding than an equivalent (J-2S orbiter) series-burn system.

We thus concluded that we would be justified in not considering the flyback booster in any further technical or risk comparison and, hence, removed that system from the subsequent evaluation process.

- *Series-Burn vs RAO Evaluation* – In the next step, we compared the series-burn configuration to RAO and attempted to resolve the major configuration issues confronting us there:

  - Series-burn vs RAO
  - J-2S SSME vs SSME-all-the-way
  - Number of orbiter engines (three vs four)

  We attempted to resolve these issues on equivalent configurations. Thus, for the series- vs parallel-burn evaluation, we compared the SSME orbiter configurations of the two systems. The other issues were dealt with relative to equivalent configurations within each system.

  The summary evaluation, which aimed at resolving the series-burn vs RAO issue is shown in Figure 3 and reproduced here for convenience as Figure 31.

  - Equivalent System Performance – The first part of the evaluation considers the factors in which the two systems are essentially equivalent. For the reasons discussed under

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RAO controllability, we have assumed booster TVC may be required for RAO when comparing it to the series-burn system. (This adds approximately 250,000 lb in GLOW and $200M to the DDT&E of the RAO system.) Thus, no technical advantage accrues to either system on the basis of lower booster propulsion system complexity, nor do we feel that the DDT&E cost differential is significant once the additional cost of booster TVC development is added to the RAO costs. Abort capability is not a significant discriminator, since both systems can abort either back to the launch site or to orbit and do not require development of an alternate landing site.

	Series SSME/BRB 	RAO SSME/BRB 	
Lower DDT&E, $B	√ 4.35	√ 4.02 + Bstr TVC	STANDOFF
Requires TVC	√ –	√ –	
Better Abort Capability (No Alt Ldg Site Reqd)	√ –	√ –	
More Practical/Lower Cost SRM, $M/Flight	20	√ 17	FAVORS RAO
Lower Booster Inert Weight, K Lb	1080	√ 2 x 370	
Simpler Booster Separation	√ 1	2	FAVORS SERIES
Cleaner Orbiter/Booster Interface	√ –	–	
Lower Payload Sensitivity, Lb/%	√ 3183	3380	
Lower Cost of Payload Assurance, $/% Wt Increase	√ 13	25	
Light Orbiter (Inert Wt), K Lb	√ 155	167	

Fig. 31 Evaluation Summary

– RAO Favorable Factors – The factors favoring RAO are shown in the middle portion of Figure 31. Both systems have SRM backoff capability, but the RAO, being lighter than the series-burn configuration, has a backoff potential to a four-1207 solid-rocket booster system at a lower cost per flight than the three-156-in. or six-1207 SRMs required for backoff from the series-burn BRB.

The fact that the BRB for the RAO is smaller is self-evident, because total inert RAO booster weight is somewhat lower and, furthermore, the RAO booster consists of two equal-size modules. We have not, as yet, determined any specific factors which impose an upper limit on the practical recovery weight of the BRB, but feel that the lower inert weight tends to reduce booster development risk and recoverability problems.

– Series-Burn Favorable Factors – The lower portion of Figure 31 addresses the factors favoring the series-burn system.

The separation and interface complexity of the RAO relative to a series-burn system were discussed in some detail under "RAO Control and Separation." Clearly, the series-burn configuration offers a technically cleaner and less complex separation and control function.

Payload sensitivities of the two systems relative to a percent change in the system inerts are shown in Figure 32. Because RAO has a somewhat heavier orbiter and HO tank, and because the parallel-burn concept is quite sensitive to changes in the inert weight of these elements, the comparison favors the series-burn system, in the sense that the latter shows about 7% lower payload loss if the inert weights should increase.

Both systems have been sized at design points off the GLOW bucket. This off-optimum design allows for the possibility of recovering payload capability (lost through inert weight increases) by simply increasing the HO tank size and leaving all other configuration elements unchanged. We have defined this capability as "potential payload margin," because it is not provided inherently by initial tank or booster oversizing but can be realized downstream in the development program – if necessary – with minimum cost and schedule impact. We do pay an initial cost penalty, however, for selecting a design point away from the minimum GLOW point; this DDT&E cost is shown in Figure 33. Combining the rate at which we lose payload (as given by the payload sensitivities of Figure 32) with the cost per pound of providing a potential margin to compensate for such payload loss, yields the figure of merit (initial program cost penalty per percent of total inert weight increase) shown on the bottom row of Figure 33. Again, this favors the series-burn system.

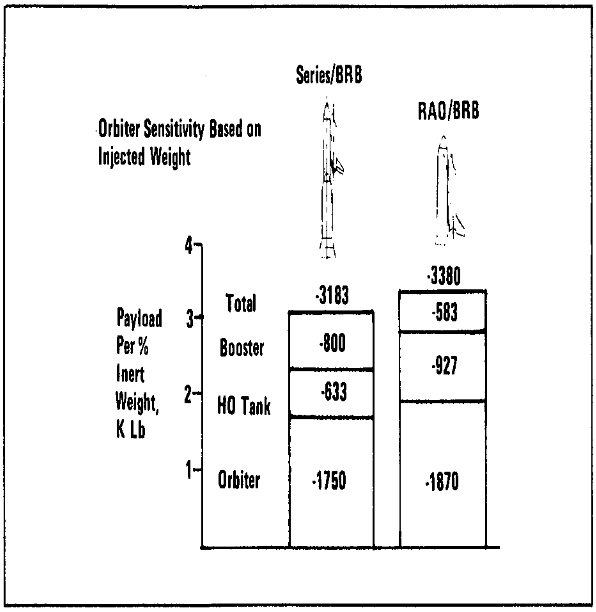

Fig. 32 Payload Sensitivities

	Series-Burn SSME/BRB	RAO SSME/BRB
DDT&E Cost to Provide Payload Margin	$35M	45
Prog Cost Δ/Percent Total Inert Weight Increase	$13M	25

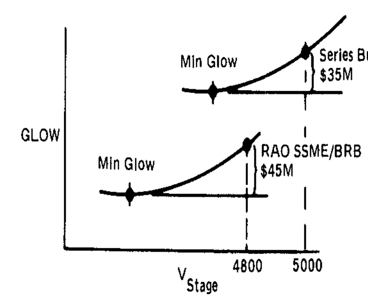

Fig. 33 Cost of Payload Assurance

CONCLUSIONS

On balance then, we conclude that costs are more or less a standoff – but, based on technical risk factors, there appears to be an edge to the series-burn system, depending on the importance attributed to, say, development of a smaller booster (but more complex system) for RAO, rather than a larger booster (but simpler system) for series-burn.

What we trade off here is development risk. The development of the ballistic booster and the overall system are the variables we considered, because the core orbiter and HO tank are essentially invariant for the two systems. The smaller, lower-inert-weight booster of the RAO configuration reduces the risk of developing that element of the system, because the problems in the critical areas of entry, water-impact loads, and recovery are diminished thereby. On the other hand, the development risk for the overall RAO system increases, as we are now confronted by other critical issues, such as separation – particularly under abort conditions – of two booster modules in proximity to the tank and orbiter, controllability of a mated configuration with unfavorable aerodynamic characteristics, tank heating problems due to orbiter plume impingement, structural problems due to high acoustic loads, and a higher sensitivity of payload loss to inert-weight increases.

We considered these RAO development risks to be somewhat higher than the risk of developing the larger series-burn booster. For purely technical reasons, we thus recommend the series-burn arrangement. We are aware, however, that the fiscal constraints on NASA are severe. In the event that a solid-booster configuration is imposed by fiscal constraints, the RAO arrangement lends itself to a potentially lower-cost-per-flight configuration. These conclusions are summarized in Figures 34 and 35.

Our conclusions relative to the J-2S vs SSME engine and number-of-engine issues can be summarized as follows. In general, we favor the J-2S/SSME approach for the series-burn configuration because of the lower development cost and risk. If the SSME-only approach is chosen, we recommend a thrust level of approximately 1.2M lb, total. For RAO, we recommend four high-thrust (450K vac, 400K SL) SSME engines at a total thrust of 1.8M lb because the higher orbiter control authority is very desirable for that configuration.

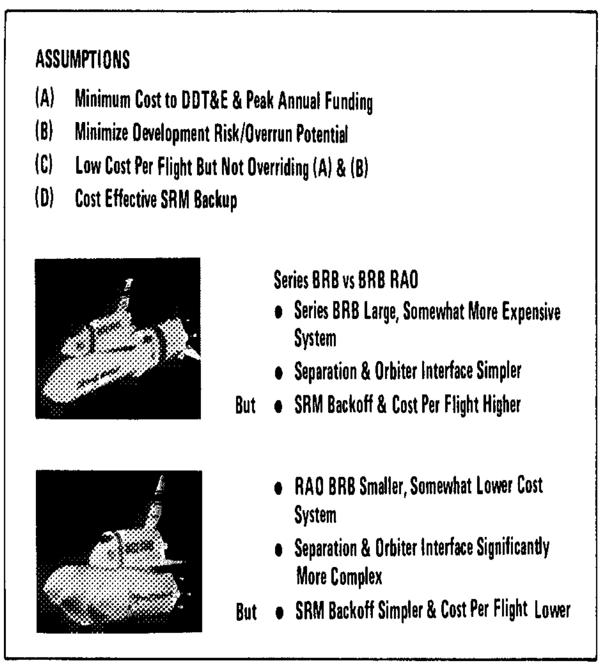

Fig. 34 Conclusions

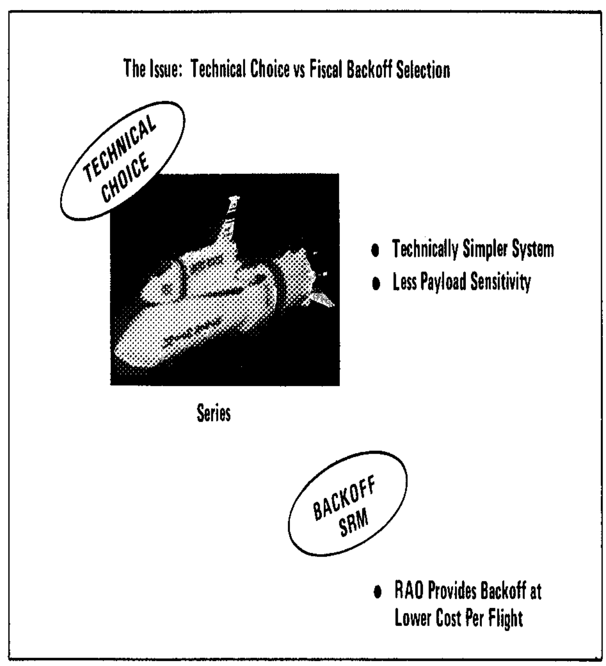

Fig. 35 Conclusions

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