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Fact Sheet for the Chairman, Committee on Science, Space, and Technology, House of Representatives

June 1988

SPACE SHUTTLE

NASA's Major Changes to Flight Hardware

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GAO

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National Security and
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June 27, 1988

The Honorable Robert A. Roe
Chairman, Committee on Science,
Space, and Technology
House of Representatives

Dear Mr. Chairman:

As requested, we have identified selected changes made by the National Aeronautics and Space Administration (NASA) to the space shuttle's flight hardware. On May 23, 1988, we briefed representatives of the House Subcommittee on Space Science and Applications on the results of our work. This report summarizes the information presented during the briefing.

Our review identified 56 changes made to the space shuttle flight hardware. Each change had an estimated cost of at least $5 million and was implemented from fiscal year 1981 through 1987. The cost of these changes totaled about $2.4 billion. Table 1 shows the breakdown of the changes by shuttle component. Appendix I shows the components of the space shuttle system. Appendix II contains a brief description of each change. Appendix III lists the individual changes under each component and their dollar values.

Table 2: Shuttle Contract Changes by Primary Justification

Primary justification	Number of changes	Value of changes (millions)	Percent of total value
51-L study	3	$ 93.1	3.9
Cost avoidance	2	16.0	0.7
Demonstrate capability	10	1,040.8	43.1
Improve reliability	10	370.6	15.4
Increase capability	12	428.9	17.8
Investigate capability	2	13.4	0.6
Make it work	5	42.8	1.8
Obsolescence	4	221.9	9.2
Safety	8	185.9	7.7
Total	56	$2,413.4	100.2[a]

[a]More than 100 percent due to rounding.

Examples of changes are provided below to better illustrate some of the justification categories.

An example of a "make it work" change is the modifications to the wing structure for the last two orbiters built, that is, orbiter vehicle (OV)-103 and OV-104. In this case, the orbiters' wings were enhanced to ensure the capability to withstand higher than anticipated aerodynamic loads and to increase the parameters during which the orbiters could be launched. Because the ability to withstand these loads was a performance requirement for the orbiters, these modifications were necessary to make the orbiter work as originally expected.

An example in which a hardware change was made to replace an obsolete component is the development and production of block II controllers[1] for the space shuttle main engines. In this case, production of block I controllers was no longer possible because many of the parts needed to produce the controller were no longer available. NASA issued a change order to develop a block II controller to replace the block I hardware. The block II controllers will be

[1]An electronics package mounted on each main engine. It contains two digital computers with associated electronics that control all main engine components and operations.

Table 4: Flight Hardware Changes Before and After the 51-L Accident By Primary Justification

Primary justification	Preaccident			Postaccident		
	Number of changes	Value of changes (millions)	Percent of total value	Number of changes	Value of changes (millions)	Percent of total value
51-L study		N/A		3	$ 93.1	8.6
Cost avoidance	1	$ 9.0	0.7	1	7.0	0.6
Demonstrate capability	6	551.6	41.5	4	489.2	45.1
Improve reliability	2	19.8	1.5	8	350.8	32.4
Increase capability	12	428.9	32.3	0	-	-
Investigate capability	0	-	-	2	13.4	1.2
Make it work	3	31.8	2.4	2	11.0	1.0
Obsolescence	3	208.7	15.7	1	13.2	1.2
Safety	4	79.6	6.0	4	106.3	9.8
Total	31	$1,329.4	100.1[a]	25	$1,084.0	99.9[b]

[a]More than 100 percent due to rounding.

[b]Less than 100 percent due to rounding.

Appendixes VIII and IX list the changes before and after the 51-L accident in each primary justification category, respectively.

OBJECTIVE, SCOPE, AND METHODOLOGY

Our objective was to identify the types of changes that have been made to the space shuttle and NASA's reasons for making them. As requested, we focused on enhancements that (1) were made to flight hardware, (2) had an estimated or definitized cost of at least $5 million each, and (3) were implemented from fiscal year 1981 through 1987. We reviewed changes made to the shuttle hardware components--the external tank, orbiter, solid rocket booster assembly, solid rocket motors, and space shuttle main engines. We did not evaluate the adequacy of NASA's justifications for these changes or the necessity of the changes themselves.

Other changes are occurring to shuttle hardware. At the time of our review, these potential future changes are still in the development phases of their contracts and have not

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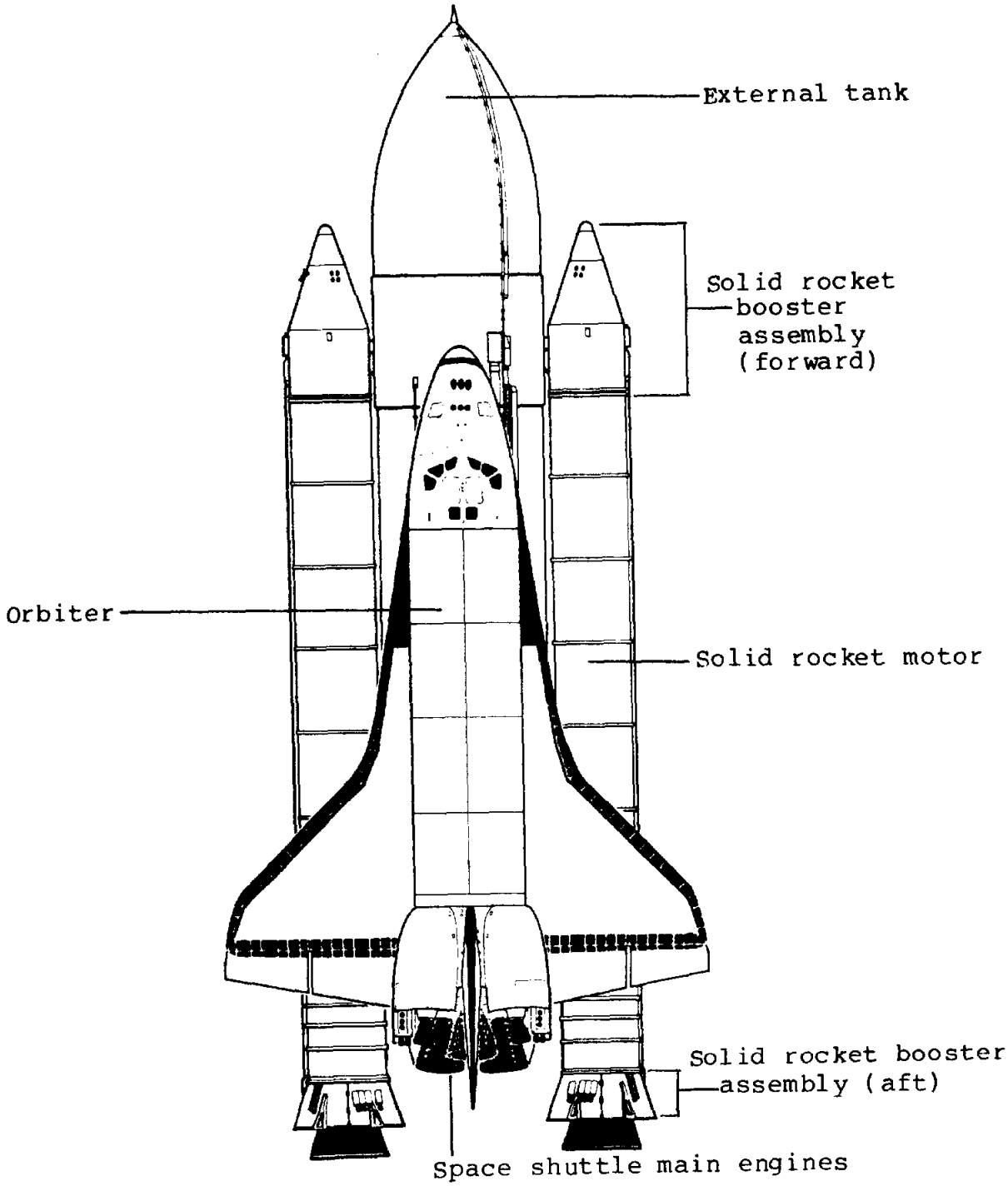
APPENDIX I

SPACE SHUTTLE COMPONENTS
(Front view)



DESCRIPTION AND STATUS OF EACH CHANGE
(as of May 20, 1988)

External tank

1. Plasma arc welding -- To improve the welding process to reduce production time. Ongoing.

Orbiter

2. Advanced thermal protection system (TPS) -- To apply fibrous refractory composite insulation (FRCI) tiles to the orbiter maneuvering pods to replace tiles and insulating blankets that were being damaged during flight. Ongoing.

3. Advanced TPS for production orbiters -- To apply lighter weight tiles (FRCI-12) and advanced flexible reusable surface insulation (AFRSI) blankets to OV-103 and OV-104. Completed.

4. Aft reaction control system (RCS) tanks -- To improve fuel flow to the thrusters. Completed.

5. Alternate inertial measurement unit (IMU) -- To replace unserviceable IMUs (due to excessive costs of repair caused by design and production obsolescence). Ongoing.

6. Brake system tests/upgrades -- To test and upgrade brakes and brake systems. Ongoing.

7. Crew egress/escape system -- To develop and install egress and escape systems on the orbiters. Ongoing.

8. Fuel cell/third substack -- To add a third fuel cell substack to extend the life of all three fuel cells and increase power capability. Completed.

9. General purpose computer (GPC) upgrade -- To replace outdated computers (parts were no longer available) with computers that have an increase in data processing speed and memory capacity. Ongoing.

10. Improved auxiliary power unit (APU) -- To extend the life of and improve servicing features of APUs. Ongoing.

11. Main propulsion system 17-inch disconnect -- To add safety latches to flapper values within the propellent lines to prevent accidental interruption of the flow of propellants from the external tank to the orbiter. Ongoing.

Solid rocket booster assembly (SRBA)

24. Aft skirt redesign modification -- To modify aft skirts in conformance with redesign specifications based on a more complete understanding of structural loads. Ongoing.

25. APU turbine wheel crack investigation -- To determine the cause of the cracks in the APU turbine wheel and develop a fracture control plan. Ongoing.

26. DFI system for STS-7 through 10 -- To gather additional flight information on the solid rocket booster (SRB) in relation to aerodynamic loads during descent. Completed.

27. DFI system for STS-26 through 31 -- To develop and provide DFI for the first six flights after flights resume. Ongoing.

28. DFI system modification -- To modify the forward skirt DFI system. Adds modifications to the DFI in change 27. Ongoing.

29. External tank (ET) attach ring -- To extend the attach ring around the entire circumference of the SRB to increase its structural capability. Ongoing.

30. Failure analysis on filament wound case static test article aft skirt -- To perform analysis and evaluation of the failed aft skirt to develop repair concepts and modify the static test article 3 aft skirt. Completed.

31. Integrated electronics assembly (IEA) -- To modify various aspects and provide additional redundancy within the IEA system. Ongoing.

32. Repair aft skirt -- To repair aft skirts from STS-1 through 6. Completed.

33. Repair failed/damaged hardware -- To repair failed and damaged SRB hardware that either failed during testing or was damaged during flight, splashdown, or recovery operations from STS-9 through 14. Completed.

34. Rework/reconfiguration of hardware for recertification -- To define and implement rework required for contractor recertification of SRB. Ongoing.

35. SRB design certification -- To perform the efforts leading to contractor certification that the design meets specifications. Ongoing.

45. Flight certification extension and development certification program -- To extend the basic full power (104 percent power level) certification to 15 missions. Also, to develop and certify (test) a 5-mission capability of the main engines at 109 percent power level operations. This change includes work on the SSME that NASA refers to as phase 1, 2, and 2+ activities. Ongoing.

46. Fusion weld specification -- To improve the welding process to reduce rework time. Ongoing.

47. Heat exchanger replacement program -- To assess units and replace those that are considered unacceptable for flight. Completed.

48. High pressure fuel turbopump (HPFTP) improvement blades -- To reduce stress on the blades through such changes as improving surface finish and coating parts of the blades. Ongoing.

49. HPFTP phase II production hardware changes -- To increase capability through such changes as reducing maintenance requirements (blade shank trailing edge cracking) and eliminating potential hot gas and high pressure hydrogen leakage into the coolant liner. Ongoing.

50. High pressure oxidizer turbopump (HPOTP) two-piece damper turbine blade -- To replace the current damper with a two-piece damper to lock all blades better and thereby reduce blade chipping, particularly at higher-power level usage. Completed.

51. Hydraulic actuators modifications -- To remove contaminants from the hydraulic actuators. NASA officials stated that the contaminants may have been the cause of the prelaunch engine shutdown on STS 41-D. Also, to replace bypass value spring guide and correct wire scuffing to meet vibration test requirements. Completed.

52. Hydraulic actuators/servo component coil modifications -- To design and manufacture improved servo valve coils to avoid the potential for malfunction of the actuators. A short circuit in the servo valve coils caused the STS 51-F launch abort. Completed.

53. Main combustion chamber (MCC) outlet elbow/splitter reinforcement -- To strengthen the elbow area welds by applying nickel plating to extend the life of the MCC. Completed.

APPENDIX III

CHANGES BY SHUTTLE COMPONENT

Change number	Description	Value of change[a] (millions)	Primary justification	Other justifications
	External tank			
1	Plasma arc welding	$ 9.0	Cost avoidance	
	Subtotal	9.0		
	Orbiter			
2	Advanced TPS	22.4	Safety	
3	Advanced TPS for production orbiters	20.8	Increase capability	Safety/Cost avoidance
4	Aft RCS tanks	10.3	Increase capability	Improve reliability/ Cost avoidance
5	Alternate IMU	40.0	Obsolescence	
6	Brake system tests/upgrades[b]	19.4	Safety	Make it work/Cost avoidance
7	Crew egress/escape system[b]	62.8	Safety	
8	Fuel cell/third substack	11.6	Increase capability	Safety
9	GPC upgrade	60.9	Obsolescence	Increase capability
10	Improved APU	26.2	Safety	Cost avoidance
11	Main propulsion system 17-inch disconnect[b]	9.9	Safety	
12	Modular auxiliary data system (MADS)	13.1	Demonstrate capability	
13	Orbiter fuel cell improvement	6.5	Increase capability	Safety
14	Orbiter modifications to accommodate Centaur vehicle	48.4	Increase capability	Safety
15	OV-102 modifications	32.7	Increase capability	
16	OV-102 Space Lab only modifications	8.3	Increase capability	Safety
17	OV-103 and subsequent vehicle wing structural modifications	7.5	Make it work	Increase capability
18	Payload bay retainer hardware	7.7	Increase capability	
19	Power reactant storage/ distribution (PRSD)	7.9	Increase capability	
20	RCS primary thruster instability protection system modifications[b]	23.8	Safety	
21	TPS/AFRSI changes	8.1	Demonstrate capability	
22	TPS upgrades on OV-102[b]	5.2	Make it work	Safety/Cost avoidance
23	TPS waterproofing	5.8	Make it work	
	Subtotal	459.3		

APPENDIX III

Change number	Description	Value of change[a] (millions)	Primary justification	Other justifications
48	HPFTP improvement blades[b]	$ 6.8	Improve reliability	Safety
49	HPFTP phase II production hardware changes	6.7	Increase capability	Improve reliability
50	HPOTP two-piece damper turbine blade[b]	16.1	Improve reliability	Safety
51	Hydraulic actuators modifications	8.8	Improve reliability	Safety
52	Hydraulic actuators/servo component coil modifications[b]	5.1	Improve reliability	Safety
53	MCC outlet elbow/splitter reinforcement[b]	35.4	Improve reliability	Safety
54	Robotic welding	11.0	Improve reliability	Cost avoidance
55	SSME flight certification program	267.3	Demonstrate capability	
56	SSME margin improvement[b]	436.0	Demonstrate capability	Safety
	Subtotal	1,197.6		
	Total	$2,413.4		

[a]Contract fees are included in the values when available.

[b]As of May 20, 1988, final negotiations for these changes have not been completed; therefore, dollar values shown are estimates.

Change number	Description	Value of change (millions)
	Space shuttle main engines	
41	Block II controller/production	$ 107.8
43	Certification at 102 percent and 102/109 percent power levels	28.5
44	FASCOS	11.6
45	Flight certification extension/ development certification program	226.5
49	HPFTP phase II production hardware changes	6.7
51	Hydraulic actuators modifications	8.8
54	Robotic welding	11.0
55	SSME flight certification program	267.3
	Subtotal	668.2
	Total	$1,329.4

APPENDIX V

Change number	Description	Value of change (millions)
	Space shuttle main engines	
42	Block II controller/thermocouple	$ 13.2
46	Fusion weld specification	7.0
47	Heat exchanger replacement program	9.8
48	HPFTP improvement blades	6.8
50	HPOTP two-piece damper turbine blade	16.1
52	Hydraulic actuators/servo component coil modifications	5.1
53	MCC outlet elbow/splitter reinforcement	35.4
56	SSME margin improvement	436.0
	Subtotal	529.4
	Total	$1,084.0

APPENDIX VII

CHANGES BY PRIMARY JUSTIFICATION

Justification	Change number	Component	Description	Value of change (millions)
51-L study	34	SRBA	Rework/reconfiguration of hardware for recertification	$ 22.1
	35	SRBA	SRB design certification	62.2
	36	SRBA	STS 51-L special studies	8.8
		Subtotal		93.1
Cost avoidance	1	ET	Plasma arc welding	9.0
	46	SSME	Fusion weld specification	7.0
		Subtotal		16.0
Demonstrate capability	12	Orbiter	MADS	13.1
	21	Orbiter	TPS/AFRSI changes	8.1
	26	SRBA	DFI system for STS-7 through 10	8.1
	27	SRBA	DFI system for STS-26 through 31	36.6
	28	SRBA	DFI system modification	6.9
	37	SRBA	Update test aft skirt	9.7
	43	SSME	Certification at 102 percent and 102/109 percent power levels	28.5
	45	SSME	Flight certification extension/ development certification program	226.5
	55	SSME	SSME flight certification program	267.3
	56	SSME	SSME margin improvement	436.0
		Subtotal		1,040.8
Improve reliability	24	SRBA	Aft skirt redesign modification	9.9
	29	SRBA	External tank attach ring	18.9
	31	SRBA	Integrated electronics assembly	18.6
	38	SRM	Consolidate 16 changes	240.0
	48	SSME	HPFTP improvement blades	6.8
	50	SSME	HPOTP two-piece damper turbine blade	16.1
	51	SSME	Hydraulic actuators modifications	8.8
	52	SSME	Hydraulic actuators/servo component coil modifications	5.1
	53	SSME	MCC outlet elbow/splitter reinforcement	35.4
	54	SSME	Robotic welding	11.0
		Subtotal		370.6

Justification	Change number	Component	Description	Value of change (millions)
Safety	2	Orbiter	Advanced TPS	$ 22.4
	6	Orbiter	Brake system tests/upgrades	19.4
	7	Orbiter	Crew egress/escape system	62.8
	10	Orbiter	Improved APU	26.2
	11	Orbiter	Main propulsion system 17-inch disconnect	9.9
	20	Orbiter	RCS primary thruster instability protection system modifications	23.8
	44	SSME	FASCOS	11.6
	47	SSME	Heat exchanger replacement program	9.8
		Subtotal		185.9
		Total		$2,413.4

APPENDIX VIII

Justification	Change number	Component	Description	Value of change (millions)
Make it work	17	Orbiter	OV-103 and subsequent vehicle wing structural modifications	$ 7.5
	32	SRBA	Repair aft skirt	14.4
	33	SRBA	Repair failed/damaged hardware	9.9
		Subtotal		31.8
Obsolescence	5	Orbiter	Alternate IMU	40.0
	9	Orbiter	GPC upgrade	60.9
	41	SSME	Block II controller/production	107.8
		Subtotal		208.7
Safety	2	Orbiter	Advanced TPS	22.4
	6	Orbiter	Brake system tests/upgrades	19.4
	10	Orbiter	Improved APU	26.2
	44	SSME	FASCOS	11.6
		Subtotal		79.6
		Total		$1,329.4

Justification	Change number	Component	Description	Value of change (millions)
Make it work	22	Orbiter	TPS upgrades on OV-102	$ 5.2
	23	Orbiter	TPS waterproofing	5.8
		Subtotal		11.0
Obsolescence	42	SSME	Block II controller/thermocouple	13.2
		Subtotal		13.2
Safety	7	Orbiter	Crew egress/escape system	62.8
	11	Orbiter	Main propulsion system 17-inch disconnect	9.9
	20	Orbiter	RCS primary thruster instability protection system modifications	23.8
	47	SSME	Heat exchanger replacement program	9.8
		Subtotal		106.3
		Total		$1,084.0

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APPENDIX IX

POSTACCIDENT CHANGES BY PRIMARY JUSTIFICATION

Justification	Change number	Component	Description	Value of change (millions)
51-L Study	34	SRBA	Rework/reconfiguration of hardware for recertification	$ 22.1
	35	SRBA	SRB design certification	62.2
	36	SRBA	STS 51-L special studies	8.8
		Subtotal		93.1
Cost avoidance	46	SSME	Fusion weld specification	7.0
		Subtotal		7.0
Demonstrate capability	27	SRBA	DFI system for STS-26 through 31	36.6
	28	SRBA	DFI system modification	6.9
	37	SRBA	Update test aft skirt	9.7
	56	SSME	SSME margin improvement	436.0
		Subtotal		489.2
Improve reliability	24	SRBA	Aft skirt redesign modification	9.9
	29	SRBA	External tank attach ring	18.9
	31	SRBA	Integrated electronics assembly	18.6
	38	SRM	Consolidate 16 changes	240.0
	48	SSME	HPFTP improvement blades	6.8
	50	SSME	HPOTP two-piece damper turbine blade	16.1
	52	SSME	Hydraulic actuators/servo component coil modifications	5.1
	53	SSME	MCC outlet elbow/splitter reinforcement	35.4
		Subtotal		350.8
Investigate capability	25	SRBA	APU turbine wheel crack investigation	8.2
	30	SRBA	Failure analysis on FWC static test article aft skirt	5.2
		Subtotal		13.4

PREACCIDENT CHANGES BY PRIMARY JUSTIFICATION

Justification	Change number	Component	Description	Value of change (millions)
Cost avoidance	1	ET	Plasma arc welding	$ 9.0
		Subtotal		9.0
Demonstrate capability	12	Orbiter	MADS	13.1
	21	Orbiter	TPS/AFRSI changes	8.1
	26	SRBA	DFI system for STS-7 through 10	8.1
	43	SSME	Certification at 102 percent and 102/109 percent power levels	28.5
	45	SSME	Flight certification extension/ development certification program	226.5
	55	SSME	SSME flight certification program	267.3
		Subtotal		551.6
Improve reliability	51	SSME	Hydraulic actuators modifications	8.8
	54	SSME	Robotic welding	11.0
		Subtotal		19.8
Increase capability	3	Orbiter	Advanced TPS for production orbiters	20.8
	4	Orbiter	Aft RCS tanks	10.3
	8	Orbiter	Fuel cell/third substack	11.6
	13	Orbiter	Orbiter fuel cell improvement	6.5
	14	Orbiter	Orbiter modifications to accommodate Centaur vehicle	48.4
	15	Orbiter	OV-102 modifications	32.7
	16	Orbiter	OV-102 Space Lab only modifications	8.3
	18	Orbiter	Payload bay retainer hardware	7.7
	19	Orbiter	Power reactant storage/ distribution (PRSD)	7.9
	39	SRM	FWC	246.5
	40	SRM	Performance improvement program	21.5
	49	SSME	HPFTP phase II production hardware changes	6.7
		Subtotal		428.9

Justification	Change number	Component	Description	Value of change (millions)
Increase capability	3	Orbiter	Advanced TPS for production orbiters	$ 20.8
	4	Orbiter	Aft RCS tanks	10.3
	8	Orbiter	Fuel cell/third substack	11.6
	13	Orbiter	Orbiter fuel cell improvement	6.5
	14	Orbiter	Orbiter modifications to accommodate Centaur vehicle	48.8
	15	Orbiter	OV-102 modifications	32.7
	16	Orbiter	OV-102 Space Lab only modifications	8.3
	18	Orbiter	Payload bay retainer hardware	7.7
	19	Orbiter	Power reactant storage/ distribution (PRSD)	7.9
	39	SRM	FWC	246.5
	40	SRM	Performance improvement program	21.5
	49	SSME	HPFTP phase II production hardware changes	6.7
		Subtotal		428.9
Investigate capability	25	SRBA	APU turbine wheel crack investigation	8.2
	30	SRBA	Failure analysis on FWC static test article aft skirt	5.2
		Subtotal		13.4
Make it work	17	Orbiter	OV-103 and subsequent vehicle wing structural modifications	7.5
	22	Orbiter	TPS upgrades on OV-102	5.2
	23	Orbiter	TPS waterproofing	5.8
	32	SRBA	Repair aft skirt	14.4
	33	SRBA	Repair failed/damaged hardware	9.9
		Subtotal		42.8
Obsolescence	5	Orbiter	Alternate IMU	40.0
	9	Orbiter	GPC upgrade	60.9
	41	SSME	Block II controller/production	107.8
	42	SSME	Block II controller/ thermocouple	13.2
		Subtotal		221.9

APPENDIX VI

DEFINITIONS OF JUSTIFICATIONS

51-L study	Studies done after the 51-L accident to evaluate existing system designs and certifications.
Cost avoidance	Avoiding the high costs of repairing outdated current equipment or introducing new techniques into the manufacturing process that allow for greater efficiency and economy.
Demonstrate capability	Testing or gathering data to certify the limits of the shuttle, for example, tests to demonstrate the durability and life of the main engines, as well as force any failure modes to appear in ground tests.
Improve reliability	Changes made that improve components of the shuttle that had been functioning properly but whose reliability could be improved, that is, raising confidence levels.
Increase capability	Augment what the shuttle can do, for example, provide more lift or allow it to carry something that it could not carry before the change.
Investigate capability	Work that is done to learn why a shuttle system did not function as designed.
Make it work	Changes to make the shuttle work the way it should, that is, correct aspects such as tiles that had not been fully functioning as designed or as necessary.
Obsolescence	New equipment was necessary because the equipment in use or the parts to service the equipment were no longer available. The current equipment is working properly, except for normal wear and tear.
Safety	Changes to make the shuttle safer.

POSTACCIDENT CHANGES BY COMPONENT

Change number	Description	Value of change (millions)
	Orbiter	
7	Crew egress/escape system	$ 62.8
11	Main propulsion system 17-inch disconnect	9.9
20	RCS primary thruster instability protection system modifications	23.8
22	TPS upgrades on OV-102	5.2
23	TPS waterproofing	5.8
	Subtotal	107.5
	Solid rocket booster assembly	
24	Aft skirt redesign modification	9.9
25	APU turbine wheel crack investigation	8.2
27	DFI system for STS-26 through 31	36.6
28	DFI system modification	6.9
29	External tank attach ring	18.9
30	Failure analysis on FWC static test article aft skirt	5.2
31	Integrated electronics assembly	18.6
34	Rework/reconfiguration of hardware for recertification	22.1
35	SRB design certification	62.2
36	STS 51-L special studies	8.8
37	Update test aft skirt	9.7
	Subtotal	207.1
	Solid rocket motor	
38	Consolidate 16 changes	240.0
	Subtotal	240.0

PREACCIDENT CHANGES BY COMPONENT

Change number	Description	Value of change (millions)
	External tank	
1	Plasma arc welding	$ 9.0
	Subtotal	9.0
	Orbiter	
2	Advanced TPS	22.4
3	Advanced TPS for production orbiters	20.8
4	Aft RCS tanks	10.3
5	Alternate IMU	40.0
6	Brake system tests/upgrades	19.4
8	Fuel cell/third substack	11.6
9	GPC upgrade	60.9
10	Improved APU	26.2
12	MADS	13.1
13	Orbiter fuel cell improvement	6.5
14	Orbiter modifications to accommodate Centaur vehicle	48.4
15	OV-102 modifications	32.7
16	OV-102 Space Lab only modifications	8.3
17	OV-103 and subsequent vehicle wing structural modifications	7.5
18	Payload bay retainer hardware	7.7
19	Power reactant storage/distribution (PRSD)	7.9
21	TPS/AFRSI changes	8.1
	Subtotal	351.8
	Solid rocket booster assembly	
26	DFI system for STS-7 through 10	8.1
32	Repair aft skirt	14.4
33	Repair failed/damaged hardware	9.9
	Subtotal	32.4
	Solid rocket motor	
39	FWC	246.5
40	Performance improvement program	21.5
	Subtotal	268.0

APPENDIX III

Change number	Description	Value of change[a] (millions)	Primary justification	Other justifications
	Solid rocket booster assembly			
24	Aft skirt redesign modification[b]	$ 9.9	Improve reliability	Safety
25	APU turbine wheel crack investigation[b]	8.2	Investigate capability	Improve reliability
26	DFI system for STS-7 through 10	8.1	Demonstrate capability	
27	DFI system for STS-26 through 31[b]	36.6	Demonstrate capability	Safety
28	DFI system modification[b]	6.9	Demonstrate capability	Safety
29	External tank attach ring[b]	18.9	Improve reliability	Safety
30	Failure analysis on FWC static test article aft skirt[b]	5.2	Investigate capability	
31	Integrated electronics assembly[b]	18.6	Improve reliability	Safety
32	Repair aft skirt	14.4	Make it work	Cost avoidance
33	Repair failed/damaged hardware	9.9	Make it work	Cost avoidance
34	Rework/reconfiguration of hardware for recertification[b]	22.1	51-L study	Safety
35	SRB design certification[b]	62.2	51-L study	Safety
36	STS 51-L special studies[b]	8.8	51-L study	Safety
37	Update test aft skirt[b]	9.7	Demonstrate capability	Safety
	Subtotal	239.5		
	Solid rocket motor			
38	Consolidate 16 changes[b]	240.0	Improve reliability	Demonstrate capability
39	FWC	246.5	Increase capability	
40	Performance improvement program	21.5	Increase capability	
	Subtotal	508.0		
	Space shuttle main engines			
41	Block II controller/production	107.8	Obsolescence	Cost avoidance
42	Block II controller/ thermocouple	13.2	Obsolescence	Cost avoidance
43	Certification at 102 percent and 102/109 percent power levels	28.5	Demonstrate capability	
44	FASCOS	11.6	Safety	
45	Flight certification extension/ development certification program	226.5	Demonstrate capability	Safety
46	Fusion weld specification[b]	7.0	Cost avoidance	
47	Heat exchanger replacement program[b]	9.8	Safety	

54. Robotic welding -- To develop a robotic welding system capable of making high-quality welds on complex configurations within the main engines. Ongoing.

55. SSME flight certification program -- To demonstrate the life expectancy of the main engines through a test program. Completed.

56. SSME margin improvement -- To design, demonstrate (test), and certify safety changes before flights resume. This change includes product improvement for return to flight and additional phase 2 activities. Ongoing.

36. STS 51-L special studies -- To conduct engineering analyses and studies in support of the investigation of the STS 51-L accident. Ongoing.

37. Update test aft skirt -- To provide an updated aft skirt for use by the contractor in static tests. Completed.

Solid rocket motor (SRM)

38. Consolidate 16 changes -- To incorporate changes since January 1987 into one contract negotiation. Changes include improved SRM processing, improved nondestructive evaluation, additional motor test program, and lightning protection. Ongoing.

39. Filament wound case (FWC) -- To design, develop, and test a lighter weight SRM to increase shuttle payloads for flights from Vandenberg Air Force Base. Completed.

40. Performance improvement program -- To modify the SRM nozzle and case to improve payload capability. Completed.

Space shuttle main engines (SSME)

41. Block II controller/production -- To provide design and development for an improved controller using current technology and components. Certain components of the existing controller are obsolete and no longer manufactured. Completed.

42. Block II controller/thermocouple -- To modify the controller to provide dual thermocouple capability. The thermocouple could be used with the current temperature sensors or a potential new sensor. Ongoing.

43. Certification at 102 percent and 102/109 percent power levels -- To demonstrate the power level capability of the main engines. Completed.

44. Flight acceleration cut-off system (FASCOS) -- To develop and provide a system to sense excessive vibration in the main engines and shutdown engine operations if necessary. It is currently used to measure vibrations and indicate maintenance needs, but it is not used as an automatic shutdown system. Completed.

12. Modular auxiliary data system (MADS) -- To gather information about orbiter performance and aerodynamic loads to supplement existing developmental flight instrumentation (DFI) information obtained during earlier flights. Completed.

13. Orbiter fuel cell improvement -- To modify fuel cell heaters and add safety instrumentation. Completed.

14. Orbiter modifications to accommodate Centaur vehicle -- To add features and equipment to OV-099 and OV-104 in preparation for accepting, boosting, and deploying the Centaur vehicle. Program canceled prior to flight use.

15. OV-102 modifications -- To make OV-102 more similar to OV-103 and OV-104 by reducing weight and modifying some equipment including cockpit upgrading and structural strengthening. Completed.

16. OV-102 Space Lab only modifications -- To accommodate Space Lab. Completed.

17. OV-103 and subsequent vehicle wing structural modifications -- To strengthen the wings to meet ascent requirements for aerodynamic loads. Ongoing.

18. Payload bay retainer hardware -- To purchase additional longeron (ribs) and keel (spine) hardware for the payload bay to support the flight schedule. Ongoing.

19. Power reactant storage/distribution (PRSD) -- To add a fifth tank set to accommodate Space Lab missions by extending mission length potential. Completed.

20. RCS primary thruster instability protection system modifications -- To prevent burn-through of thrusters by wrapping thrusters with wire detector systems. Ongoing.

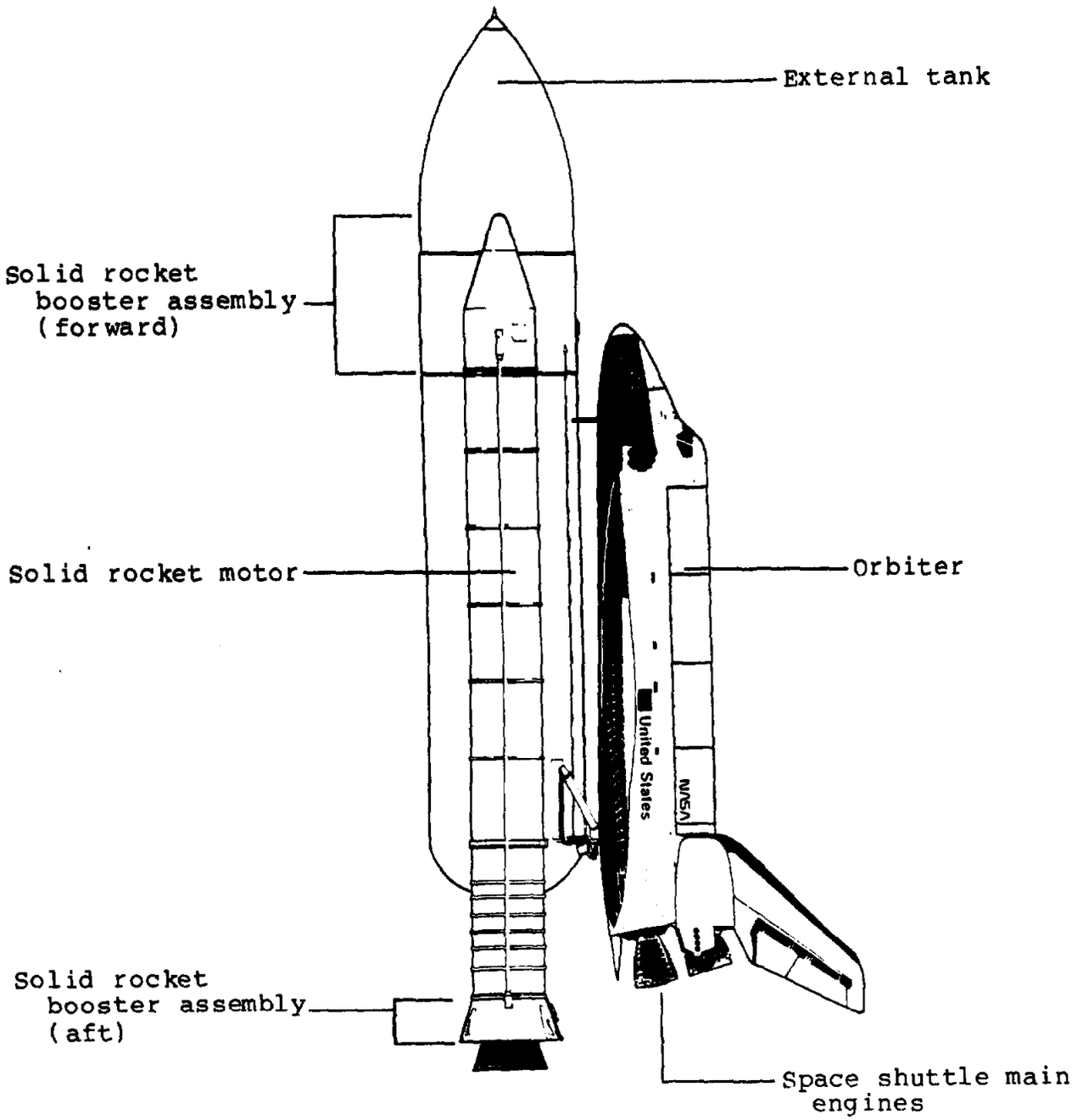
21. TPS/AFRSI changes -- To attach AFRSI blankets to OV-099 for flight testing. Completed.

22. TPS upgrades on OV-102 -- To replace damaged lower area tiles with FRCI-12 tiles. Ongoing.

23. TPS waterproofing -- To develop and implement an improved waterproofing method that includes a new waterproofing material. Ongoing.

APPENDIX I

SPACE SHUTTLE COMPONENTS
(Side view)



ABBREVIATIONS

AFRSI	Advanced flexible reusable surface insulation
APU	Auxiliary power unit
DFI	Developmental flight instrumentation
ET	External tank
FASCOS	Flight acceleration cut-off system
FRCI	Fibrous refractory composite insulation
FWC	Filament wound case
GPC	General purpose computer
HPFTP	High pressure fuel turbopump
HPOTP	High pressure oxidizer turbopump
IEA	Integrated electronics assembly
IMU	Inertial measurement unit
MADS	Modular auxiliary data system
MCC	Main combustion chamber
NASA	National Aeronautics and Space Administration
OV	Orbiter vehicle
PRSD	Power reactant storage/distribution
RCS	Reaction control system
SRB	Solid rocket booster
SRBA	Solid rocket booster assembly
SRM	Solid rocket motor
SSME	Space shuttle main engines
STS	Space Transportation System
TPS	Thermal protection system

yet resulted in any new hardware for shuttle use. Therefore, we did not include them in our study. For example, NASA has a project underway to develop an alternate turbopump for the space shuttle main engines, which is intended to increase engine capability through longer life expectancy at higher power levels and avoid costs through reduced turnaround time. This project has been budgeted for about $403 million in three increments through 1993. To date, NASA has awarded a $198.2 million development contract for the first increment.

As agreed with your representatives, we did not review changes made to launch and landing support hardware, systems integration and mission control hardware, facilities and construction, structural spares, spares, software, or the original costs of the production orbiters and OV-105, as well as costs for the production propulsion flight components.

We obtained the information in this report through an examination of contracting and project office documents at the Johnson Space Center and the Marshall Space Flight Center, as well as through discussions with NASA officials at NASA Headquarters and the two Centers. As requested, we did not obtain official agency comments on this report; however, we discussed a draft with NASA officials and incorporated their views and comments as appropriate.

Our work was performed between November 1987 and May 1988 in accordance with generally accepted government auditing standards.

As arranged with your Office, unless you publicly announce its contents earlier, we plan no further distribution of this report until 5 days after its issue date. At that time, we will send copies of this report to the Chairmen, House and Senate Committees on Appropriations and the Senate Committee on Commerce, Science, and Transportation; the Administrator, National Aeronautics and Space Administration; and other interested parties upon request.

Should you have any additional questions, please contact me at 275-4268.

Sincerely yours,

Harry R. Finley
Senior Associate Director

installed as each block I controller requires parts that can no longer be provided.

A change that "demonstrates capability" is the development and procurement of a developmental flight instrumentation system for the solid rocket boosters for Space Transportation System (STS) flights 26 through 31. This instrumentation will gather data on the performance of and the stress placed on the redesigned motors.

PREACCIDENT AND POSTACCIDENT CHANGES

Of the 56 changes, 31 were initiated before the 51-L accident on January 28, 1986, and 25 after the accident; each group of changes totaled approximately $1 billion. This information is summarized in table 3.

Table 3: Flight Hardware Changes Before and After the 51-L Accident by Component

	Preaccident			Postaccident		
Component	Number of changes	Value of changes (millions)	Percent of total value	Number of changes	Value of changes (millions)	Percent of total value
External tank	1	$ 9.0	0.7	0	-	-
Orbiter	17	351.8	26.5	5	$ 107.5	9.9
Solid rocket booster assembly	3	32.4	2.4	11	207.1	19.1
Solid rocket motor	2	268.0	20.2	1	240.0	22.1
Space shuttle main engines	8	668.2	50.3	8	529.4	48.8
Total	31	$1,329.4	100.1[a]	25	$1,084.0	99.9[b]

[a]More than 100 percent due to rounding.

[b]Less than 100 percent due to rounding.

Appendixes IV and V list the individual changes before and after the 51-L accident by component, respectively. The distribution of changes by primary justification is shown in table 4.

Table 1: Changes to the Shuttle by Component

Component	Number of changes	Value of changes (millions)	Percent of total value
External tank	1	$ 9.0	0.4
Orbiter	22	459.3	19.0
Solid rocket booster assembly	14	239.5	9.9
Solid rocket motor[a]	3	508.0	21.0
Space shuttle main engines	16	1,197.6	49.6
Total	56	$2,413.4	99.9[b]

[a]Does not include NASA's settlement with the contractor for the redesign of the solid rocket motor joint following the 51-L (Challenger) accident, since it was not the result of a formal change order. According to a NASA official, the contractor is redesigning the joint to meet original performance specifications, and NASA will pay for the costs of the redesign work but will not pay a fee to the contractor.

[b]Less than 100 percent due to rounding.

NASA'S REASONS FOR MAKING SHUTTLE HARDWARE CHANGES

We grouped NASA's reasons for making the 56 changes into 9 general justification categories, as summarized in table 2. Detailed definitions of each of these categories appear in appendix VI.

Many of the shuttle changes are justified by more than one category. Appendix III shows primary as well as other justifications for the changes. Appendix VII expands on the information in table 2 by listing the changes included in each primary justification category.