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Safety Analysis of Parallel Versus Series Propellant Loading of the Space Shuttle

Final Report, Volume II: Technical Discussion

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SAFETY ANALYSIS OF PARALLEL VERSUS SERIES PROPELLANT LOADING OF THE SPACE SHUTTLE

FINAL REPORT, VOLUME II: TECHNICAL DISCUSSION

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ABSTRACT

This report documents a Space Shuttle Safety Analysis Study regarding the relative magnitude of hazards of series versus parallel propellant loading within a 75-minute time period.

It was concluded that, under the conditions of equal total propellant loading time, parallel loading is potentially more hazardous than series loading; this is due to (1) the greater explosion potential of the propellants in the vehicle tanks during the entire loading operation, and (2) the simultaneous relatively high flow rates in the loading lines. However, it was also determined that by reducing the parallel loading time to approximately one-half the series loading time, the higher hazard associated with parallel loading could be reduced to an acceptable value. Since this would require a system size approximately equal to that necessary for series loading, the economic advantage of parallel loading would be negated.

However, if it is assumed that only a relatively small percentage of vehicles will require a short reaction time on the launch pad, then, the lower cost of parallel loading can be realized by designing a smaller system and operating it in series for a normal loading time of 150 minutes. Where minimum reaction time is required, the propellants could be loaded in approximately 75 minutes by operating the same system in parallel at a relatively small additional risk.

PREFACE

This study was initiated as Subtask 2, Dual Propellant Loading of the Space Shuttles to NASA Study C-II, Advanced Missions Safety Studies. Other studies in this series are: Subtask 1, TNT Equivalency Study, Aerospace Report No. ATR-71(7233)-4; and, Subtask 3, Orbiting Propellant Depot Safety Study, Aerospace Report No. ATR-71(7233)-3.

The study was supported by NASA Headquarters and managed by the Advanced Missions Office of the Office of Manned Space Flight. Mr. Herbert Schaefer, as the study monitor, provided guidance and counsel that significantly aided this effort.

The results of the study are presented in two volumes: Management Summary Report (Volume I) and Technical Discussion (Volume II). The Management Summary Report (Volume I) presents a brief, concise review of the study content, and summarizes the principal conclusions and recommendations. The Technical Discussion (Volume II) is the principal volume. It provides a discussion of the relative magnitude of hazards of a series versus parallel propellant loading system for the Space Shuttle. Suggested design and procedural criteria that would tend to minimize hazards are provided where appropriate. Also included is a consideration of equalizing the hazard levels associated with the two loading system concepts. A composite system, capable of either series or parallel operation, is suggested as desirable.

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I. INTRODUCTION

A feasibility and economic study of a propellant loading system required to meet a two-hour launch reaction time for the Space Shuttle was conducted during 1969, using Saturn V propellant loading system experience (Ref. 1). Feasible propellant loading systems were synthesized to provide loading within a one-hour time period as required to conduct pre-launch operations within two hours. The relative cost of simultaneous (parallel) loading of the LH_2 and LO_2 propellants was compared to the cost of sequential (series) loading of the two propellants. It was concluded that, for the one-hour loading time period, parallel loading would allow cost reductions of $12 million or approximately 30 percent of the total system cost assuming a new propellant loading facility.

Since the method of propellant loading employed on all presently known vehicles using LH_2 and LO_2 has been in series, hazards created by parallel loading required extensive evaluation. Since parallel loading has the advantage of smaller flows to load within a given time period, a study of the relative hazards was conducted with the purpose of assessing the relative hazards of the two loading methods and establishing the feasibility of providing compensating provisions for potential failures. It was believed that in this manner, data could be derived in this study to determine which method of loading to use.

Flight vehicle requirements such as propellant quantities and loading times were based on a contractor proposal for the Phase B Space Shuttle Study. Propellant loading systems were synthesized based on the previous study (Ref. 1) which included loading sequences, propellant loading rates, system schematics, and comparisons of a new system versus a modification of KSC Pad 39 system.

The hazard analysis included identification of the types of hazards, their possible causes and effects, and the gross criticality of the hazard. The relative criticality of the effects in a series and a parallel method loading system was then assessed by comparing the relative probability, time criticality, and consequences of the identified failures for the two methods. Where differences in criticality in the two methods of loading occurred, the hazards and possible effects were summarized and the feasibility of compensating for the respective differences in hazards was evaluated. If compensation was found feasible, the necessary provisions were indicated. Consideration was given to both the ground propellant loading hazards and the hazard potential of the fluids stored in the vehicle.

II. FLIGHT VEHICLE BASELINE

The North American Rockwell Proposal to accomplish Phase B Space Shuttle Study was utilized to establish the vehicle baseline (Ref. 2). Although this was but one of several alternate configurations considered, it was judged that the selection of only one particular configuration would not significantly alter the results and conclusions considering the level of the depth of this study.

The baseline system configuration, shown in Fig. 1, consists of a booster-orbiter combination sized to a gross lift-off weight limit of 3.5 million lb. The orbiter configuration has a 200-mi cross-range and a payload capability of 45,000 lb. Alternate configurations with a high cross-range orbiter should not materially affect the results of the study. The booster and orbiter are mated in the configuration shown in Fig. 1, and both use LO_2/LH_2 propellants. It is assumed that there are no interconnecting propellant lines between the orbiter and booster, or between the orbiter and payload.

The main propulsion propellant storage for the booster consists of one LH_2 tank and one LO_2 tank. Both tanks are made of 2219-T81 aluminum alloy. The LH_2 tank is insulated internally with closed-cell polyurethane foam with a layer of fiberglass reinforcement to protect the surface of the foam from damage and to inhibit permeation of the foam by the LH_2. The LO_2 tank is uninsulated; a dry nitrogen purge is required to inhibit ice formation on the tank during pre-launch servicing. Thermally driven, natural convective circulation is utilized for the LO_2 manifolds to eliminate geysering and to precondition all but the 15-ft-long individual engine feed ducts. It should be noted that the LO_2 tank is located in the forward section of the booster. The booster is 257 ft in overall length with the pad support points 218 ft from the nose. The top of the LO_2 tank is at an elevation head of 184 ft above the launch pad support level. The booster also requires LH_2/LO_2 for its attitude control propulsion system and auxiliary power unit.

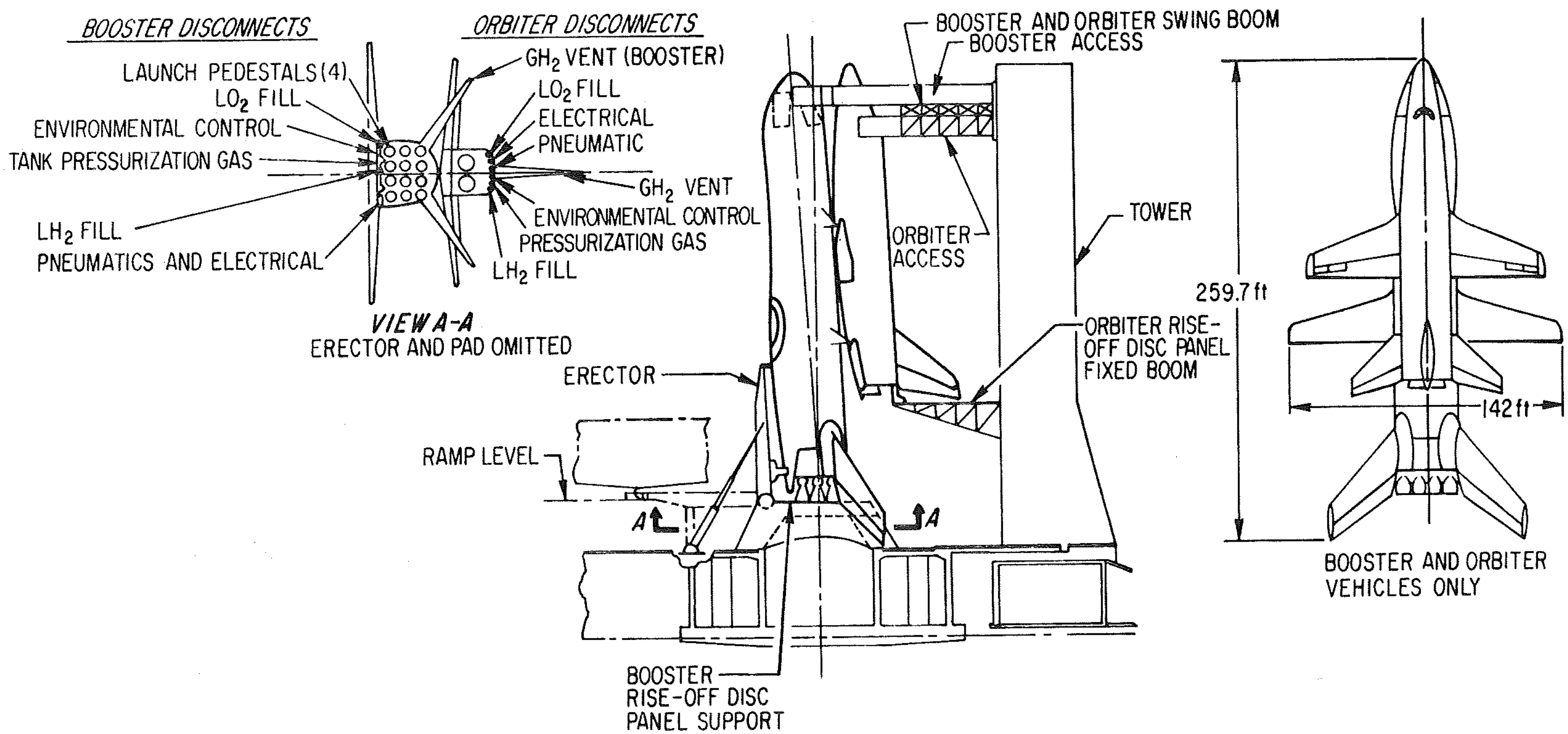

Fig. 1. Integrated Booster/Orbiter Configuration

The basic propellant storage system configuration for the orbiter is similar to that described for the booster except that two tanks are used for storage of the main propulsion system LO_2. Tank materials and insulation techniques are the same as those used on the booster. In addition to the main propulsion system, LH_2/LO_2 propellants are also required for the orbiter attitude control and orbit maneuvering propulsion systems.

Table 1 indicates the quantities of propellants required by the booster and orbiter. Although propellant loading for payloads are not considered a part of this study, in consideration of a worse case situation for propellant loading systems requirements, the payload is assumed to be loaded for a resupply mission as a propellant tanker. For comparison, the quantities required by the Saturn V vehicle have been indicated. It should be noted that although more than twice as much liquid hydrogen is required by the Space Shuttle as by the Saturn V vehicle, an almost inverse situation exists with regards to liquid oxygen. In order to synthesize the loading system requirements, it was assumed that no special conditioning such as subcooling of the propellants was required. It was also assumed that the interfaces between the propellant loading system and the vehicle exist at the base of each segment.

Table 1. Total Vehicle Propellant Loads

Space Shuttle

Stage	LH_2				LO_2			
	m^3	t†	gals	lb (x 10^6)	m^3	t†	gals	lb (x 10^6)
Booster	2330	165	615,300	0.363	767	875	202,760	1.930
Orbiter	533	37.7	140,860	0.083	189	211	48,900	0.464
B/O Total	2863	202.7	756,160	0.446	956	1086	251,660	2.394
Tanker	257	18.2	67,700	0.040	18	20	4,670	0.044
B/O/T Total	3120	220.9	823,860	0.486	974	1106	256,330	2.438

Saturn V Vehicle (Comparison)

Stage	LH_2				LO_2			
	m^3	t†	gals	lb (x 10^6)	m^3	t†	gals	lb (x 10^6)
SIC	----	-----	------	-----	1310	1490	345,000	3.280
S II	1040	73.5	275,000	0.162	326	371	80,000	0.816
S IV B	277	19.5	73,000	0.043	76	86.3	20,000	0.190
Total	1317	93.0	348,000	0.205	1712	1947.3	451,000	4.286

†t = metric tons

††Tanker will contain either LH_2 or LO_2, not both.

III. PROPELLANT LOADING SYSTEM MODELING

A. PROPELLANT STORAGE

Table 2 indicates the propellant storage requirements. The storage capacity was sized for the loading and launching of two vehicles without requiring replenishment of the storage tanks. The first vehicle consists of a booster, orbiter, and an orbiter payload. The payload consists of propellant tanks that would be used for the orbiting propellant depot. The storage tanks were sized to contain quantities of fluid that would be required to load the vehicles, plus sufficient quantities to compensate for boiloff, other losses, and potential hold periods. It was assumed that the first vehicle to be launched would be the primary vehicle, and that the second vehicle would serve as a potential rescue mission craft. This second vehicle would perform the rescue on a vehicle of the first type and would therefore neither contain a payload such as a tanker, nor the additional propellants required by the tanker. It was also assumed that the hold period for the rescue mission would be kept to a maximum of 45 min, since this launch would be taking place under emergency conditions.

Based upon the configurations shown, the total quantities stored in the tanks, including 20 percent contingencies, would be 2.38 and 0.86 million gallons of LH_2 and LO_2, respectively. If a completely new facility were to be built, storage tanks with these capacities would be required. If Cape Kennedy Pad 39 were to be modified, an additional storage capacity of 1.55 million gallons of LH_2 would have to be added to the existing capacity of 0.85 million gallons. No storage capacity would have to be added to the LO_2 system, since the existing capacity of 0.90 million gallons is adequate to meet space shuttle requirements.

B. LOADING TIMELINES

The propellant loading system timeline for series loading and parallel loading are illustrated in Figs. 2 and 3, respectively. Both timelines are based on the 75-min loading time discussed in Ref. 2. For the series loading

Table 2. Estimated Propellant Storage Requirements

Sized for Two Firings Without Replenishment

	LH_2 (gal)	LO_2 (gal)
First Vehicle		
Booster-Orbiter-Tanker	824,000	257,000
Chilldown and Trapped Losses	61,000	38,000
Six Hours (Maximum Hold)	250,000	120,000
Second Vehicle		
Booster-Orbiter	757,000	252,000
Chilldown and Trapped Losses	61,000	38,000
45-Minute Hold	32,000	15,000
Two Vehicle Total	1,985,000	720,000
Contingency (20 Percent)	397,000	144,000
Storage Requirements	2,382,000	864,000
Modification of Pad 39		
Existing	850,000	900,000
Additional Storage Required	1,550,000	NONE
All New PLS (New Site)	2,400,000	900,000

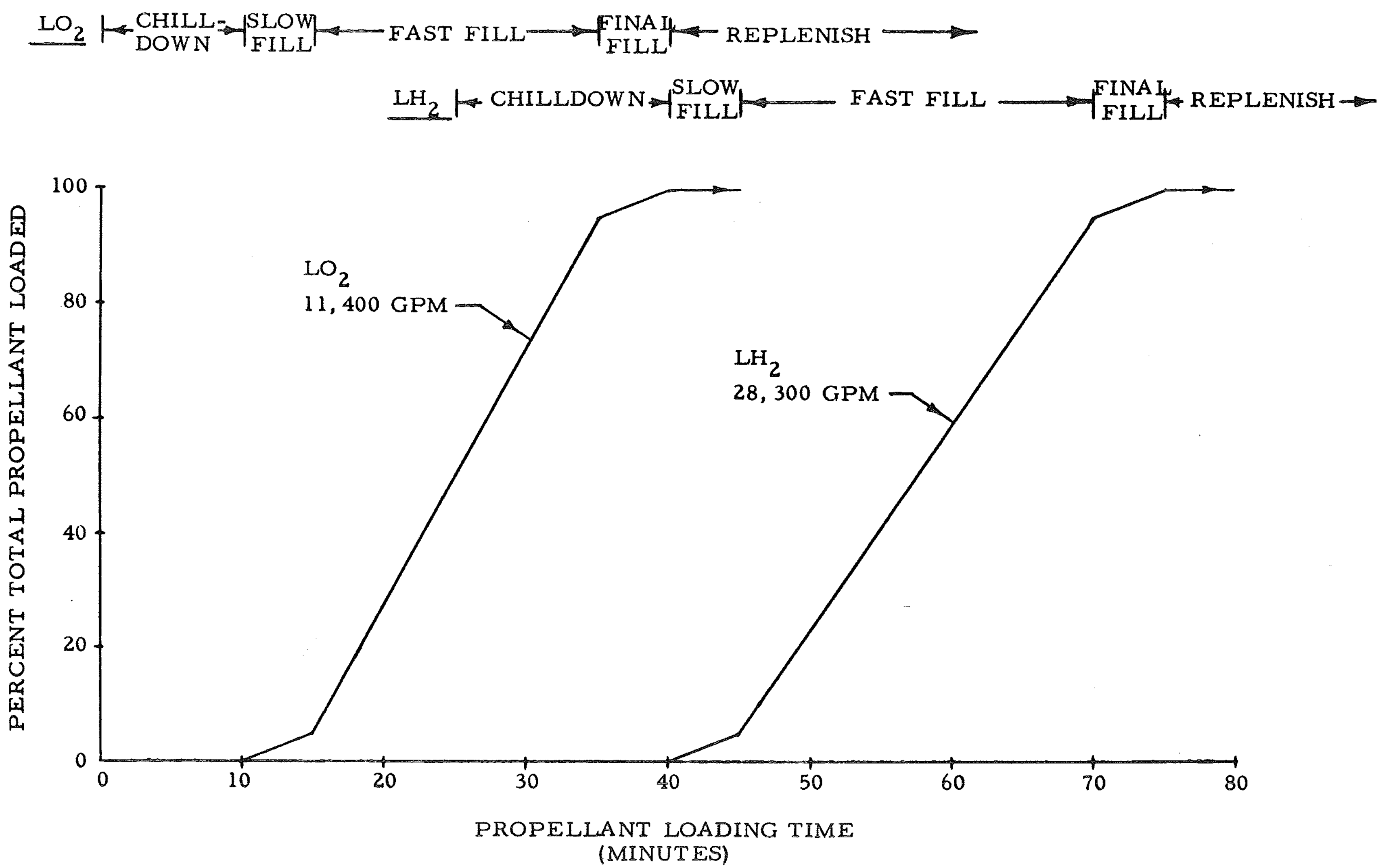

Fig. 2. Series Propellant Loading

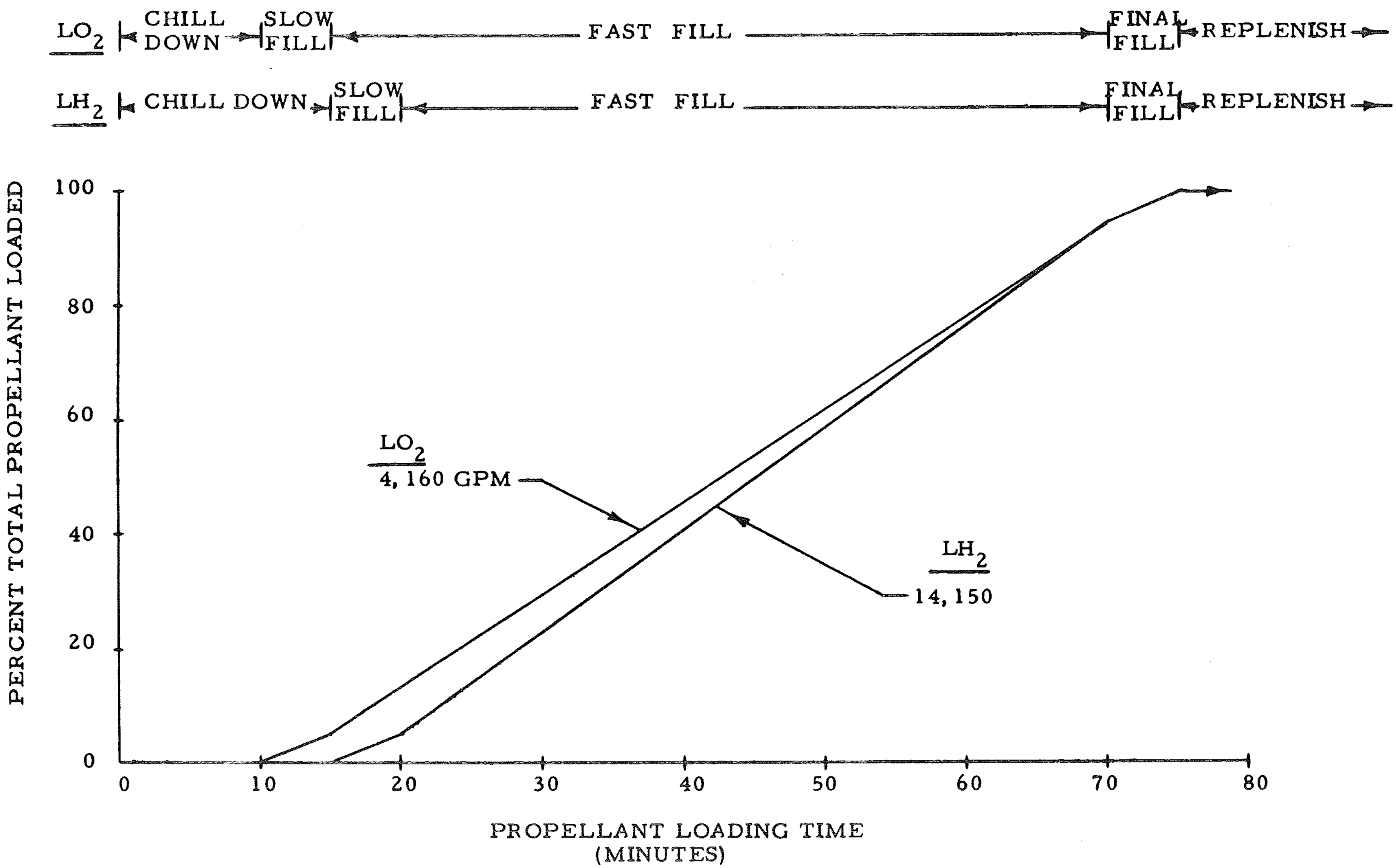

Fig. 3. Parallel Propellant Loading

sequence, it can be noted that simultaneous fast-fill of LH_2 and LO_2 does not occur, and chilldown of the LH_2 system takes place during rapid loading of the LO_2. Because of this, it is of importance to recognize the major differences between series and parallel loading.

During parallel loading, simultaneous rapid loading of the LH_2 and LO_2 occurs; whereas in series, the rapid loading is performed sequentially. However, the respective flows of the LH_2 and LO_2 are higher in series.

C. SYSTEM SIZING AND CONCEPTS

Table 3 summarizes the loading times shown on the timelines from which the flow rates were computed. These flow rates were then used to size the propellant loading system lines used to transfer the fluids from storage tanks to the vehicles. The sizing was based on obtaining a minimum cost system as discussed in Ref. 1.

1. LO_2 System

A schematic for a concept of a "new" LO_2 loading system is depicted in Fig. 4. It can be noted that the storage tank has a capacity of 0.90 million gallons. Pressurization for transfer is provided by pumps based on the study in Ref. 1, which indicated that a pumping system would be more economical than a pressurized transfer system. A small pump and a 4-in. vacuum jacketed line are provided for low flow conditions. A larger pump and uninsulated line, sized at 12 in. for the series method of loading and 8 in. for the parallel method, are provided for rapid loading. The drain basin is used to receive drainage from the lines and boiloff gases from both the lines and the vehicles. Draining of vehicle tanks, if required, would consist of utilizing the fill lines as drain lines and returning the LO_2 to the storage tank.

Figure 5 shows a Cape Kennedy Pad 39 LO_2 system modified to perform the same function as the new system. Whereas the new system would have a 4-in. vacuum jacketed low-flow line, the existing Pad 39 system incorporates a 6-in. vacuum jacketed line. For rapid flow conditions, the

Table 3. Propellant Loading Requirements

Parameter	Parallel Loading		Series Loading	
	LO_2 System	LH_2 System	LO_2 System	LH_2 System
Loading Time	75 Minutes		75 Minutes	
Preconditioning and Childown (Vehicle Tanks)	10 min	15 min	10 min	(15)
Slow Fill 0% - 5%	5 min	5 min	5 min	5 min
Fast Fill 5% - 95%	55 min	50 min	20 min	25 min
Final Fill 95% - 100%	5 min	5 min	5 min	5 min
Maximum Flow Rates (Total)	4,160 GPM	14,150 GPM	11,430 GPM	28,296 GPM
Booster Fill	3,325 GPM	11,315 GPM	9,144 GPM	22,637 GPM
Final Fill	835 GPM	2,835 GPM	2,286 GPM	5,659 GPM
Line Sizes				
Modified System (Pad 39)				
Existing	14" UN & 6" VJ	One 10" VJ	14" UN & 6" VJ	One 10" VJ
Modification	None	None	None	One 10" VJ
New System	8" UN & 4" VJ	12" VJ	12" UN & 4" VJ	14" VJ

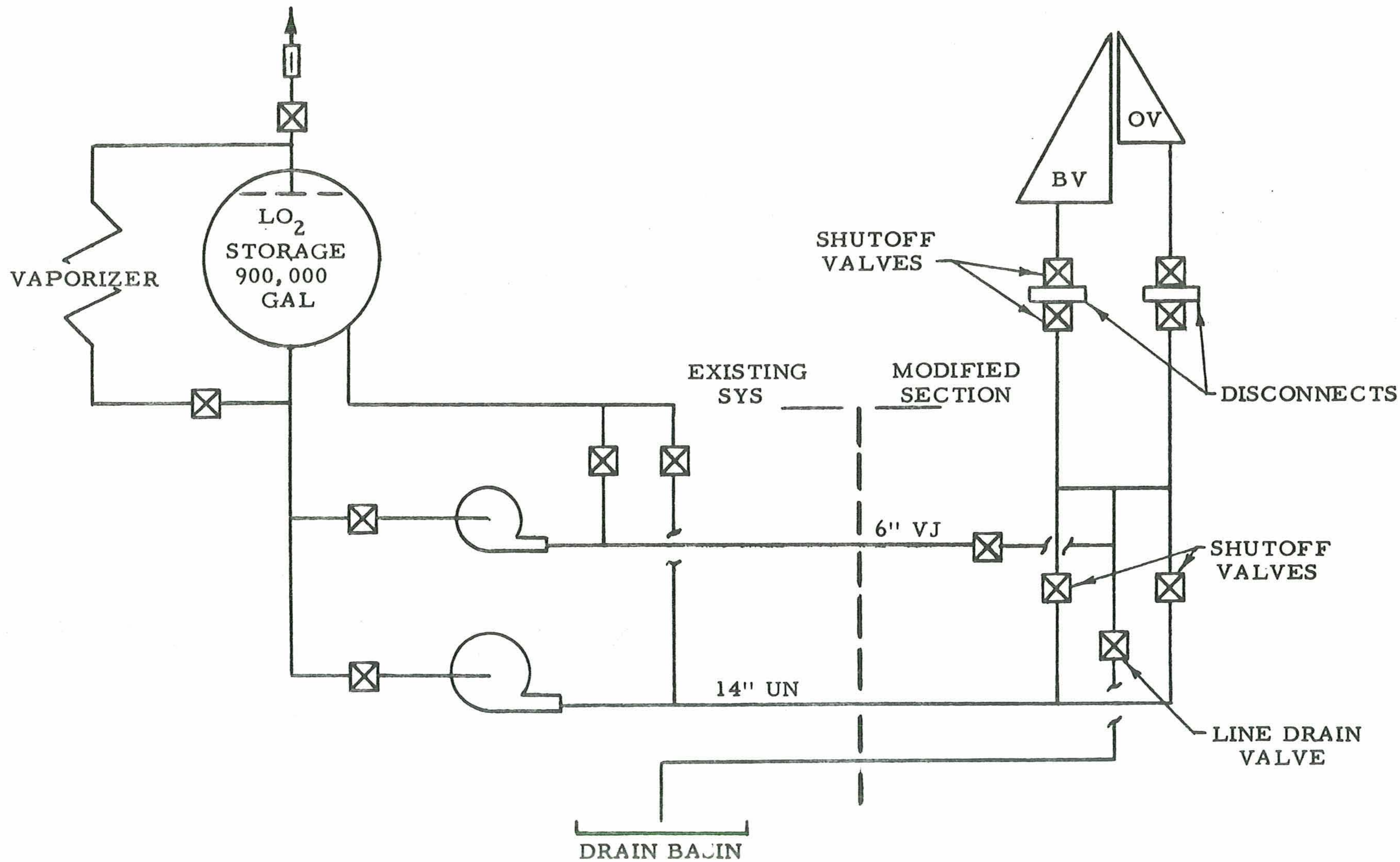

Fig. 4. Schematic of New LO_2 Loading System

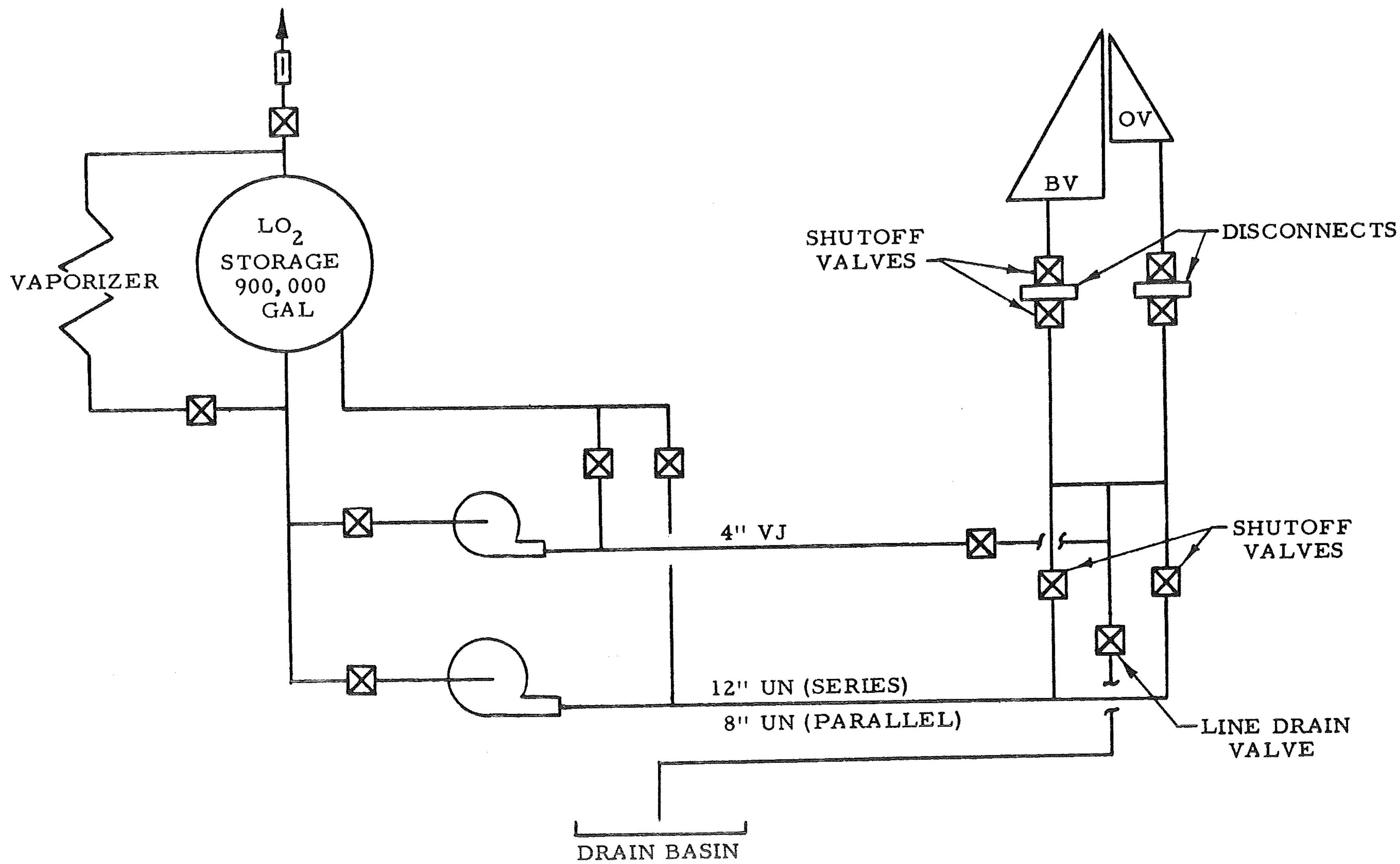

Fig. 5. Schematic of Modified LO_2 Loading System

existing 14-in. uninsulated line at Pad 39 is sized slightly larger than the new system would require for series operations.

With the exception of the somewhat larger lines incorporated within the Pad 39 modified system, relatively little difference in the area of potential hazard is noted between the new LO_2 system and the modified Pad 39 LO_2 system since the same flow rates wo[illegible] prevail. Therefore, in further analysis of hazards, no distinction will be made between the new and the modified system.

2. LH_2 System

Figure 6 shows a concept for a new LH_2 loading system, again based on the analysis performed in Ref. 1. The storage capacity of the system is 2.4 million gallons, and transfer is by means of pressurization of the storage tank using vaporizers. For series transfer, the 14-in. vacuum jacketed line would be required; whereas, parallel transfer would require a 10-in. vacuum jacketed line. The fill and drain system indicated is used to drain lines, and also provides disposal of boiloff gases similar to the concept of the LO_2 system. Drainage of the vehicle would be accomplished by utilizing the fill lines back into the LH_2 storage tank.

For comparison, a modified Pad 39 system is shown in Fig. 7. It can be noted that a new storage capacity of 1.55 million gallons is added to the existing storage capacity of 0.85 million gallons. The combined capacity of the two storage tanks is equal to that of the new system. In order to obtain the required rapid flow rates, a new 10-in. vacuum jacketed line must be added to the existing 10-in. vacuum jacketed line at Pad 39. The total capacity of the two 10-in. lines would be equivalent to the 14-in. single line for the new system.

From the standpoint of potential hazard of the two LH_2 systems, insufficient difference was noted between the modified and new system concepts to allow distinction in hazard level; therefore, both the modified and the new LH_2 system will also be treated equally in the hazard analysis that follows.

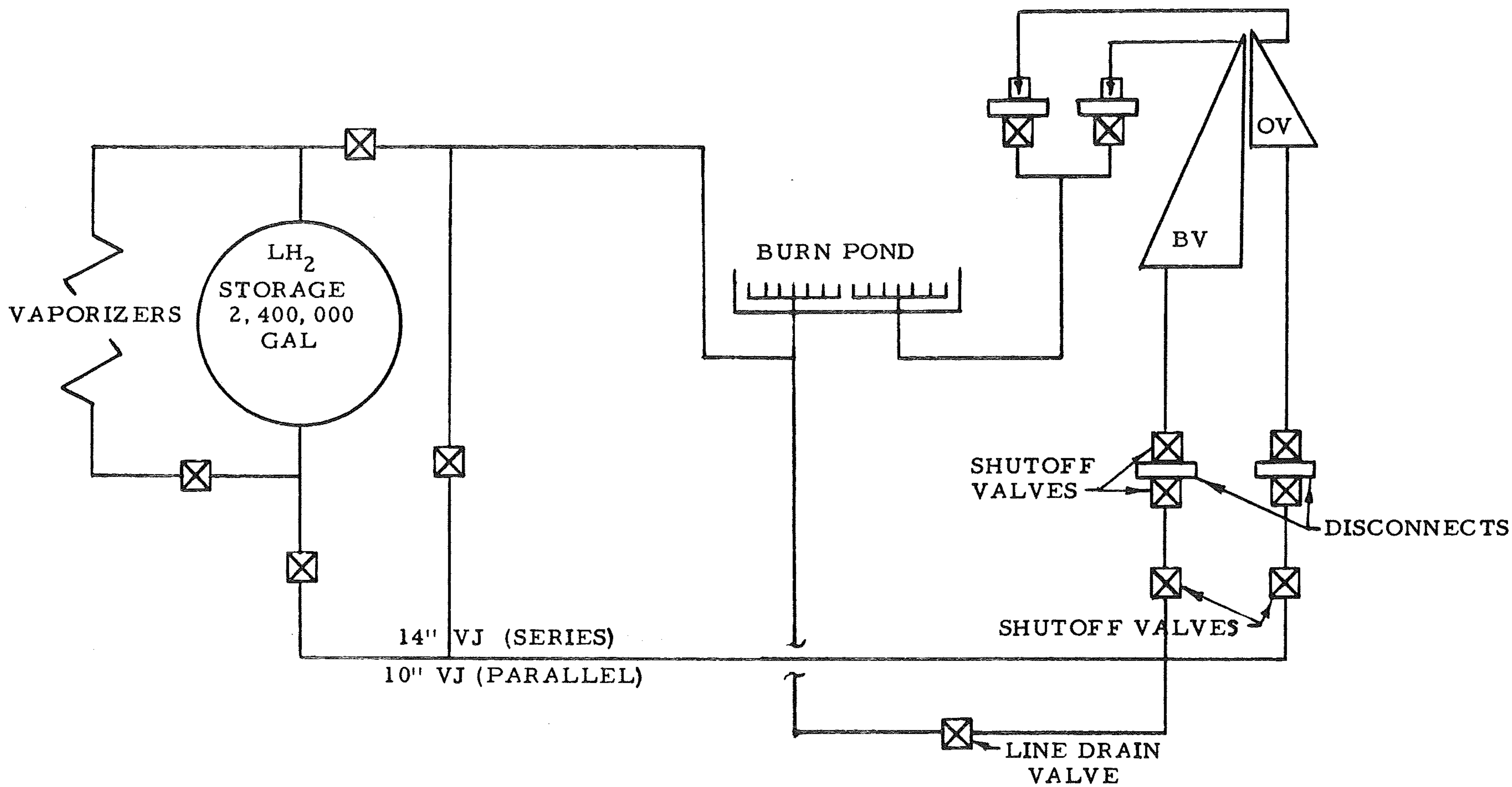

Fig. 6. Schematic of New LH_2 Loading System

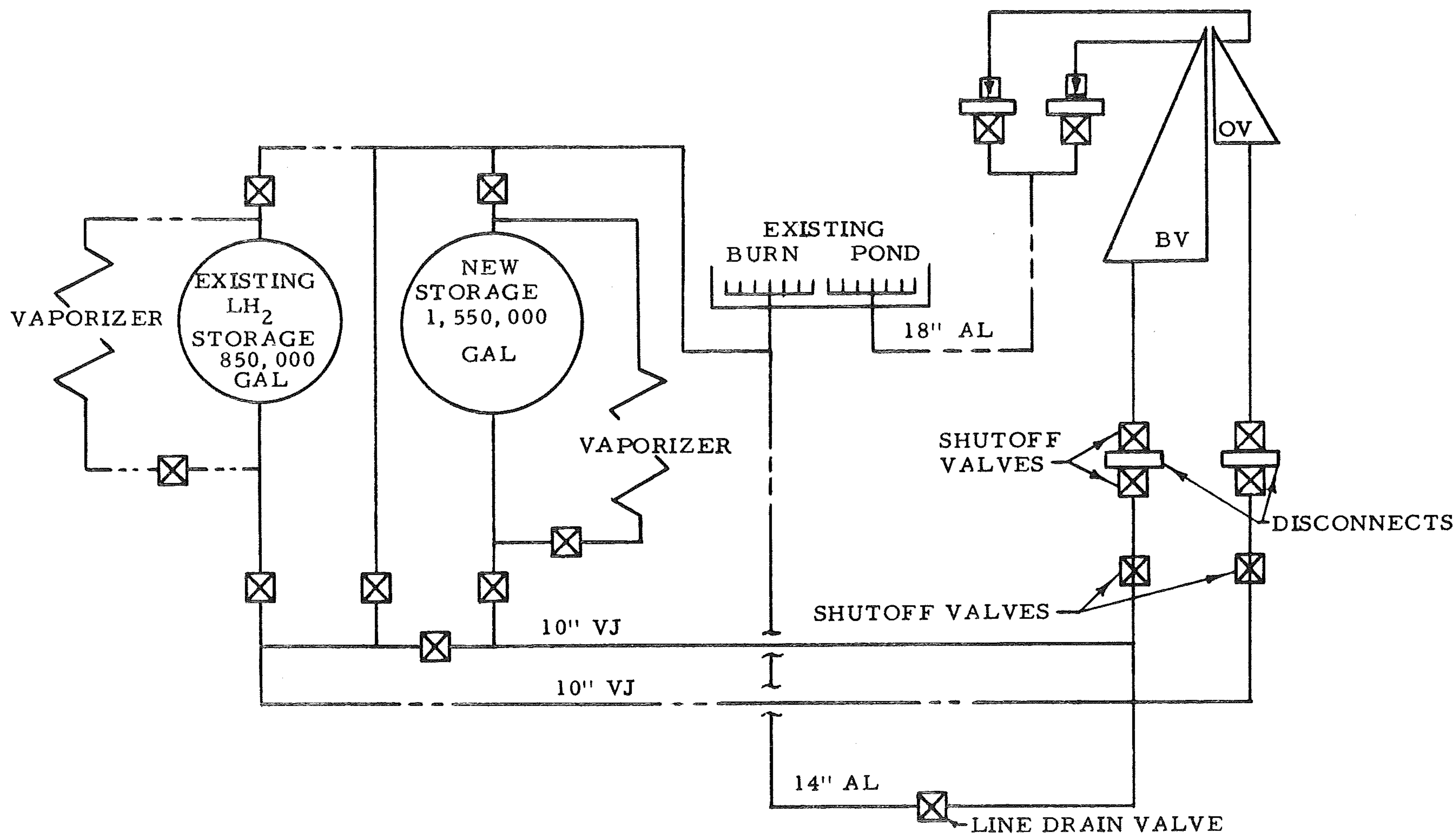

Fig. 7. Schematic of Modified LH_2 Loading System

IV. HAZARD ANALYSIS

A. APPROACH

The basic approach used in conducting the hazard analysis was to identify potential hazards and then to determine possible causes and effects of those hazards (Ref. 3). It was assumed that the series method of operation and the type of systems synthesized are acceptably safe, since they have been patterned after types of systems currently in use. The approach was therefore based upon assessing the relative difference in hazards between series and parallel loading.

The gross level of each hazard was classified in one of the following categories in accordance with NASA Office of Manned Space Flight Directive No. 1 SPD-1A (Ref. 4):

"A" - Safety Catastrophic Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will severely degrade system performance, and cause subsequent system loss, death, or multiple injuries to personnel.

"B" - Safety Critical - Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will cause equipment damage or personnel injury, or will result in a hazard requiring immediate corrective action for personnel or system survival.

"C" - Safety Marginal - Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will degrade system performance but which can be counteracted or controlled without major damage or any injury to personnel.

"D" - Safety Negligible - Condition(s) such that personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will not produce system functional damage or personnel injury.

The relative criticality of the hazard effects was evaluated using a system outlined in Ref. 5. The criticality classes were designated as:

"P" - Probability of failure

"T" - Time criticality relative to reaction time available

"C" - Consequence of the failure if uncompensated for

Each of these three classes was considered independently and the following ranking was used. Where the criticality of either parallel or series was greater, the symbol "G" was placed in the respective column. Where the criticality was considered to be the same, the symbol "S" was used, and where it was considered to be less, the symbol "L" was placed in the respective column. In this manner, an assessment of the relative criticality of hazards in parallel or series loading methods was indicated relative to the effect of a given hazard.

B. HAZARD ASSESSMENT

Tables 4a through 4h indicate an assessment of all hazards and possible causes and effects that were considered in this study. The following explanation is offered to allow an understanding of the rationale used in arriving at the assessments shown in these tables. The left hand column labeled "Hazards" defines in alphabetical order the types of hazards which might occur. The next column labeled "Possible Causes" defines the events in the operation of the system that potentially could cause the hazard. The column labeled "Possible Effects" indicates the effect on the system if the event that causes the potential hazard occurs.

In some cases a specific condition is listed as a hazard; in others, as a cause or effect. For example, an explosion may be an effect of "Structural Damage or Failure" listed as a hazard; conversely, under the hazard labeled "Explosion," structural damage may be listed as one of the effects. At the same time, an explosion may be the cause of structural damage. The interrelationship of hazards, causes, and effects makes the elimination of duplication difficult. However, redundancy was considered preferable to inadequate coverage of hazards.

The column labeled "Hazard Assessment" classifies the relative criticality of the different effects. The column labeled "Rationale" was added in order to explain the logic that was used to arrive at the relative assessment of criticality where differences between series and parallel loading methods appeared. As an example, in Table 4a under the hazard labeled "Acceleration," a possible cause of "opening or closing the shutoff valves" is noted. Rapid operation of a valve at relatively high flow rates can produce a pressure surge, however, a pressure surge by itself does not necessarily present a hazard in a properly designed system. For this reason, the gross hazard level was classified as "C-Safety Marginal" with its associated definition. From a consideration of criticality relative to probability of failure, time, and consequence, it was considered that the given pressure surge would have equal criticality in a parallel or series system. Therefore, no differences between parallel and series loading methods relative to this effect were noted.

The same opening or closing of the shutoff valve and pressure surge can result in an excessive pressure in the system. This effect was labeled as "B-Safety Critical" since an excessive pressure can produce damage unless compensating devices are built into the system. As previously noted, the consequences of such an effect are rated on the basis of the uncompensated failure. It was judged that the probability and time criticality of the excessive pressure effect would be approximately equal in both the parallel and series systems. However, the consequence was considered to be greater in the series system, since for the series operation higher rapid load flow rates are required to perform the loading. A given closing time of a valve would, as a result, produce a higher system pressure in the series system than in the parallel system.

The effect labeled "Structural Failure of Fluid Containing Components" can be explained in a similar manner. The gross hazard rating in this case is "A" since a structural failure is considered a catastrophic condition. The probability of occurrence in either series or parallel was judged to be

Table 4a. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
ACCELERATION (ANY FLUID MASS UNDERGOING A CHANGE IN VELOCITY.)	CHANGE IN FLOW CONTROL VALVE POSITION	PRESSURE SURGES	C	S	S	S	S	S	S	
	OPENING OR CLOSURE OF SHUTOFF VALVES	EXCESSIVE PRESSURE	B	S	S	L	S	S	G	HIGHER FLOW RATES
	CHANGE IN LINE OR PASSAGE SIZE	DEFLECTION OF PLUMBING AND COMPONENTS	C	S	S	S	S	S	S	
	CHANGE IN FLUID DENSITY OR CHANGE OF PHASE OF CRYOGEN	STRUCTURAL FAILURE OF FLUID CONTAINING COMPONENTS	A	S	L	L	S	G	G	HIGHER FLOW RATES AND LESS TIME TO REACT
	PUMPING ACTION	CAVITATION	B	S	S	S	S	S	S	
	LOSS OF CONTROL OF FLUID FLOW									
CONTAMINATION (ENTRY OF CONTAMINATES INTO SYSTEM)	INCORRECT OPERATING PROCEDURES	ENTRY OF AIR AND OTHER CONTAMINATES INTO SYSTEM	C	S	S	S	S	S	S	NO SIGNIFICANT DIFFERENCE NOTED.
	POOR MAINTENANCE PROCEDURES	FROZEN AIR MAY DETONATE IN LH_2 SYSTEM CAUSING STRUCTRUAL DAMAGE AND FIRE	A	S	S	S	S	S	S	
	CONTAMINATED FLUID SUPPLY	CLOGGING AND/OR BLOCKING OF FILTERS, ORIFICES, VALVES, REGULATORS, LINES, ETC.	C	S	S	S	S	S	S	
	CONTAMINATED PURGE GAS SUPPLY	SCORING AND ABRASION OF CLOSELY FITTED MOVING SURFACES.	C	S	S	S	S	S	S	
	NEGATIVE PRESSURE IN SYSTEM									
	FILTRATION SYSTEM OVERLOADED									
	SOLVENT RESIDUAL									
	POOR QUALITY CONTROL									

A - CATASTROPHIC
B - CRITICAL
C - MARGINAL
D - NEGLIGIBLE

P - PROBABILITY OF FAILURE
T - REACTION TIME CRITICALITY
C - CONSEQUENCE CRITICALITY

G - GREATER
S - SAME
L - LESS

approximately the same. The consequence of the structural failure was assessed as greater in the series system than in the parallel system, since the series lines are larger and higher flow rates exist. Since a structural failure in one of the lines of the series system would result in more spillage of fluids, the reaction time was also judged greater.

The hazard labeled "Contamination" pertains to the entry of contaminants into the system. It was judged that the criticality of the effects showed no significant difference in either the series or parallel methods of loading. Similarly, no significant differences were noted under the hazard labeled "Corrosion" shown in Table 4b. The lack of significant differences in these areas can be explained by noting that the somewhat larger line size and the higher rapid flow rates of the series system have no direct relationship to the effects of these hazards.

In the area of "Electrical" hazards, a difference was noted for the effect of interrupting the communications due to an electrical failure. If such interruption of communications should occur in the series method of loading, a greater time criticality was assigned. The higher flow rate that exists in that method would require a faster reaction time to limit the consequence of the failure. It was assumed that the interruption of communication could occur at the same time as another type of failure, however, the probability of this type of occurrence should be quite low.

The hazard area of "Explosion" shows some of the more significant differences between the series and parallel methods of loading (Table 4c). As an example, for the effect labeled "Structural Damage of Propellant Loading System" the gross hazard level of this failure was assessed as class "A" since it has the potential of being catastrophic. The probability of failure in either the series or parallel method of loading would be approximately the same. If a single failure occurred, i.e., a failure in one of the fluid lines, the consequence of failure and time criticality would be greater in the series system. In this case, however, it is assumed that an explosion will be produced by the structural damage. If an explosion occurs during the

Table 4b. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
CONT. CONTAMINATION (INTERNAL GENERATION OF CONTAMINATES)	METAL AND/OR ELASTOMER PARTICLES	FRICTION BETWEEN SLIDING SURFACES.	C	S	S	S	S	S	S	NO SIGNIFICANT DIFFERENCI NOTED.
	CONCENTRATING OF CONTAMINATES	VALVES SEATING INTERFERENCE AND DAMAGE.	C	S	S	S	S	S	S	
		IMPACT OF FAST MOVING PARTICLES MAY IGNITE IN LO_2 SYSTEM CAUSING STRUCTURAL DAMAGE AND FIRE	A	S	S	S	S	S	S	
CORROSION (DETERIORATION OF MATERIAL OR SIGNIFICANT CHANGE IN MECHANICAL PROPERTIES)	INCOMPATIBLE MATERIALS AS DESIGNED	CONTAMINATION OF THE SYSTEM.	C	S	S	S	S	S	S	NO SIGNIFICANT DIFFERENCE NOTED.
	LEAKAGE	BINDING OF MOVING SURFACES.	C	S	S	S	S	S	S	
	DAMAGED PROTECTIVE SURFACES OR COATINGS.	REDUCTION IN MATERIAL STRENGTH.	B	S	S	S	S	S	S	
	ELECTROLYTIC CORROSION (DISSIMILAR METALS)	DEGRADATION IN PHYSICAL AND CHEMICAL PROPERTIES.	B	S	S	S	S	S	S	
	CONDENSATING OF ATMOSPHERIC MOISTURE									
	SALT ATMOSPHERE									
ELECTRICAL (SHOCK, THERMAL, INADVERTENT ACTIVATION, POWER SOURCE FAILURE, ETC.)	CONTACT WITH LIVE CIRCUIT	PERSONNEL: ELECTROCUTION, BURNS, INTERFERENCE WITH PERFORMANCE AND ETC..	B	S	S	S	S	S	S	
	DEGRADATION, REMOVAL OR DAMAGE OF INSULATION	IGNITION SOURCE FOR DETONABLE OR COMBUSTIBLE MIXTURE OF HYDROGEN AND OXYGEN	B	S	S	S	S	S	S	
	SHORT CIRCUITS	BURNOUT AND/OR DAMAGE OF EQUIPMENT	B	S	S	S	S	S	S	

A - CATASTROPHIC
B - CRITICAL
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D - NEGLIGIBLE

P - PROBABILITY OF FAILURE
T - REACTION TIME CRITICALITY
C - CONSEQUENCE CRITICALITY

G - GREATER
S - SAME
L - LESS

Table 4c. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
CONT. ELECTRICAL	CONTAMINATION OR MOISTURE	UNTIMELY ACTIVATION OF ELECTRICAL EQUIPMENT	B	S	S	S	S	S	S	
	STRAY ENERGY SOURCES; I.E., LIGHTNING, STATIC ELECTRICITY.	INTERRUPTION OF COMMUNICATION	B	S	L	S	S	G	S	LESS TIME TO REACT FOR SERIES LOADING DUE TO POSSIBILITY OF FAILURE OF HIGH FLOW RATE.
	INADEQUATE ELECTRICAL PROTECTION.	INACTIVATION OF DETECTION AND WARNING SYSTEM.	B	S	S	S	S	S	S	
	OVERLOAD OF ELECTRICAL EQUIPMENT	LOSS OF CONTROL	A	S	S	G	S	S	L	FAIL SAFE
	LACK OF "BACK-UP" EQUIPMENT									
	LACK OF FAIL-SAFE DESIGN									
EXPLOSION (OVERPRESSURIZATION OF PRESSURE CONTAINING COMPONENTS OR EXTERNAL MIXING AND DETONATION OF H_2/O_2 LIQUID AND/OR GAS)	OVERPRESSURIZATION OF SYSTEM AND/OR COMPONENTS.	STRUCTURAL DAMAGE OF AIRBORNE VEHICLE PROPELLANT SYSTEM	A	S	S	G	S	S	L	ALTHOUGH THE PROBABILITY OF FAILURES IN BOTH SYSTEMS FOR PARALLEL LOADING IS LESS THAN FOR A SINGLE FAILURE FOR SERIES LOADING. THE CONSEQUENCE IS GREATER "IF" IT SHOULD HAPPEN SINCE TWO FLUIDS FLOW SIMULTANEOUSLY
	FAILURE OF PRESSURE RELIEF SYSTEM	STRUCTURAL DAMAGE OF PROPELLANT LOADING SYSTEM	A	S	S	G	S	S	L	
	WARMING OF "TRAPPED" CRYOGENIC LIQUIDS	GENERATION OF IMPULSE AND/OR SHOCK WAVES	B	S	S	G	S	S	L	
	FROZEN (SOLID) AIR IN LH_2 SYSTEM	INITIATION OF SECONDARY EXPLOSIONS	A	S	S	G	S	S	L	
	CONTAMINATION IN LO_2 SYSTEM (SHOCK IGNITION)	FRAGMENTATION DAMAGE TO OTHER EQUIPMENT	A	S	S	G	S	S	L	
	STRUCTURAL FAILURE OF PLUMBING AND/OR LO_2 SYSTEMS WITH IGNITION SOURCE	FIRE	A	S	S	G	S	S	L	
		INJURY TO PERSONNEL	B	S	S	G	S	S	L	

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parallel method of loading, while both fluids are flowing rapidly through the lines, it is quite feasible that structural fragmentation of one system could impact on the other. If proper compensations do not exist, mixing of the two fluids could occur. Under such a condition, the consequence of this failure would be greater in parallel than in series. A similar type of rationale and logic was used in assessing the remainder of possible explosion hazard effects, and in all cases a greater hazard was assigned to the parallel method of loading.

The hazard labeled "Fire" on Table 4d shows a possible effect of secondary explosions. For the same reasons as explained previously, the simultaneous rapid flow in the parallel method of loading produces a greater class of criticality. For the "Heat and Temperature" hazard a greater criticality is again assigned to the occurrence of an explosion under the parallel method of loading.

Table 4e defines effects that are related to the hazard of "Leakage." The longer flow time periods associated with parallel loading make leakage a somewhat greater hazard for the parallel method of loading, since more time is available for fluid to leak from the system. It should be noted that, although the flow rates are greater in series than in parallel, the operating pressures are approximately the same. Therefore, it is primarily the time period that affects the amount of fluid that would leak from a given size opening.

The effects producing the hazard labeled "Pressure" on Tables 4e and 4f vary in their relative criticality between series and parallel. As an example, if a given component of the system ruptures, the resulting hazard was considered to be higher in both probability and consequence for the series mode of operation. This was based on the reasoning that the series components are subjected to higher flow rates and are therefore considered to have a higher probability of failure, and that the consequence of such a failure, based on the amount of fluid that would spill due to the rupture, would be greater in series due to the higher flow rate. If, however, such a

Table 4d. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT: GROSS	PARALLEL			SERIES			RATIONALE
				P	T	C	P	T	C	
FIRE (REACTION OF HYDROGEN OR OTHER FUELS WITH ANY COMBINATION OF OXYGEN SOURCE	COMBUSTIBLE MIXTURE OF HYDROGEN AND OXYGEN WITH IGNITION SOURCE AVAILABLE	SECONDARY EXPLOSIONS	A	S	S	G	S	S	L	HIGHER FLOW RATES
	SHOCK IGNITION OF CONTAMINATION LH_2 AND/OR LO_2.	CONTAMINATION OF MATERIAL	C	S	S	S	S	S	S	
		ASPHYXIATION AND/OR BURNS OF PERSONNEL	A	S	S	S	S	S	S	
		HEAT AND ITS EFFECTS	B	S	S	S	S	S	S	
HEAT AND TEMPERATURE (HIGH TEMPERATURE, LOW TEMPERATURE AND TEMPERATURE VARIATION.)	INADEQUATE HEAT DISSIPATION	FIRE AND/OR EXPLOSION	A	G	S	S	L	S	S	POSSIBILITY OF TWO FLUIDS FLOWING AT THE TIME OF FAILURE
	LACK OF THERMAL INSULATION	REDUCED MATERIAL STRENGTH	C	S	S	S	S	S	S	
	CRYOGENIC FLUID LEAKAGE AND/OR SPILL	REDUCED EQUIPMENT OR COMPONENT LIFE	B	S	S	S	S	S	S	
		INCREASED EVAPORATION RATE	C	S	G	S	S	L	S	LONGER EXPOSURE TIME
		JAMMING, BINDING OR LOOSENING OF MOVING PARTS	C	S	S	S	S	S	S	
		FROSTBITE OR CRYOGENIC BURNS TO PERSONNEL	B	S	S	S	S	S	S	
		INCREASED BRITTLENESS OF CERTAIN MATERIAL	B	S	S	S	S	S	S	
		CONDENSATION OF ATMOSPHERIC MOISTURE	C	S	S	S	S	S	S	
		FORMATION OF LIQUID OR SOLID AIR	B	S	S	S	S	S	S	
		DIMENSION CHANGES OF SYSTEM COMPONENTS	C	S	S	S	S	S	S	
		HIGH STRESS LEVELS IN CERTAIN COMPONENTS	B	S	S	S	S	S	S	

A - CATASTROPHIC
B - CRITICAL
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D - NEGLIGIBLE

P - PROBABILITY OF FAILURE
T - REACTION TIME CRITICALITY
C - CONSEQUENCE CRITICALITY

G - GREATER
S - SAME
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Table 4e. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL			SERIES			RATIONALE
				P	T	C	P	T	C	
LEAKAGE (ANY SMALL UNCONTROLLED FLOW OF ANY FLUID INTO, OUT OF OR THROUGH THE SYSTEM)	CRACKS CAUSED BY STRUCTURAL FAILURE	FORMATION OF EXPLOSIVE OR FLAMMABLE MIXTURE	B	S	S	S	S	S	S	
	HOLE CAUSED BY IMPACT	LOSS OF SYSTEM FLUID	C	S	G	S	S	L	S	LONGER EXPOSURE TIME
	WELD AND/OR MANUFACTURING DEFECTS	LOSS OF SYSTEM PRESSURE	C	S	G	S	S	L	S	LONGER EXPOSURE TIME
	INADEQUATELY FITTED OR TIGHTENED PARTS	CONTAMINATION OF SYSTEM	B	S	S	S	S	S	S	
	FITTING OR CONNECTOR LOOSENED BY VIBRATION	EXPLOSION AND/OR FIRE	A	S	S	S	S	S	S	
	CORRODED METAL OR DETERIORATED SEALS, SEATS ETC.	ENTRY OF AIR INTO PORTION OF THE SYSTEM	B	S	S	S	S	S	S	
	WORN OR CONTAMINATED MATING SURFACES.	HIGH HEAT LEAK OF V-J LINE	C	S	G	S	S	L	S	LONGER EXPOSURE TIME
	EXCESSIVE PRESSURE									
	POORLY DESIGNED CONNECTIONS									
PRESSURE (HIGH PRESSURE (RELATIVE), LOW PRESSURE, AND RAPID CHANGES IN PRESSURE)	OVERPRESSURIZATION OF SYSTEM OR COMPONENTS	COMPONENT AND/OR SYSTEM RUPTURE	B	L	S	L	G	S	G	LARGER COMPONENTS AND LINES, HIGHER FLOW RATES FOR SERIES LOADING
	INADEQUATE PRESSURE RELIEF SYSTEM OR VENT	EXPLOSION	A	S	S	G	S	S	L	SAME AS EXPLOSION HAZARD
	FAULTY PRESSURE OR RELIEF VALVE	FRAGMENTATION AND PROPELLING OF COMPONENTS	A	S	S	G	S	S	L	
	WARMING OF "TRAPPED" CRYOGENIC LIQUIDS IN A CLOSED OR INADEQUATELY VENTED SYSTEM.	LINE WHIPPING (INADEQUATE RESTRAINING DEVICES)	A	S	S	S	S	S	S	MORE ENERGY DUE TO HIGHER FLOW RATES
	INADEQUATE DESIGN FOR COLLAPSING FORCES	COLLAPSE OF PRESSURE VESSEL OR STORAGE TANK	A	L	L	S	G	G	S	FLOW RATES AND REACTION TIME

A - CATASTROPHIC
B - CRITICAL
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Table 4f. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
CONT. PRESSURE	PUMPING OF FLUID	CAVITATION	B	S	S	S	S	S	S	
	VALVE OPENING OR CLOSURE	FORMATION OF VAPOR PHASE AND SUBSEQUENT COLLAPSE	B	S	S	S	S	S	S	
	EXPANSION OF FLUID THROUGH A RESTRICTION	FLUID HAMMER	B	S	L	L	S	G	G	FLOW RATES
	LOSS OF CONTROL OF FLUID FLOW	LEAKAGE OF FLUIDS	C	S	G	S	S	L	S	LONGER FLOW TIMES
		SPILLAGE OF FLUIDS	A	S	L	S	S	G	S	FLOW RATES
SHOCK (MECHANICAL AND/OR FLUID SHOCK)	IMPACT AND/OR IMPULSE	DETONATION OF EXPLOSIVE MIXTURE	A	S	S	S	S	S	S	
	EXPLOSION	DAMAGE OF EQUIPMENT, COMPONENTS AND/OR SYSTEM	B	S	S	S	S	S	S	
	ACCELERATION CHANGE OF FLOW CONTROL VALVE POSITION	DETONATION OF CONTAMINATED LIQUID	A	S	S	S	S	S	S	
	SUDDEN OPENING OF CLOSURE OF VALVE	STRUCTURAL FAILURE, DAMAGE OR RUPTURE OF SYSTEM AND/OR COMPONENT	B	S	L	L	S	G	G	FLOW RATES
		FLUID HAMMER	B	S	L	L	S	G	G	FLOW RATES
STRESS REVERSALS (VIBRATING OR OSCILLATING EQUIPMENT AND/OR FLUID)	CYCLIC CHANGES IN STRESS FROM TENSION TO COMPRESSION AND THE REVERSE; CHILLDOWN OPERATIONS; PRESSURE CYCLING	STRUCTURAL FAILURE AND/OR DAMAGE AS A RESULT OF MATERIAL FATIGUE	A	S	S	G	S	S	L	TWO FLUIDS FLOWING

A - CATASTROPHIC
B - CRITICAL
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failure would result in an explosion, the hazard is considered to be greater in parallel, because the potential fragmentation could cause a failure in the other rapidly flowing fluid lines, resulting in the mixing of fluids.

For the effect resulting in line whipping, it was considered that the hazard was greater in series due to the higher flow rate of that method.

For the effect labeled "Collapse of Pressure Vessel or Storage Tank," the hazard was judged more critical for the series method of loading. The higher flow rates of that system create a higher probability of too rapid chill of the vehicle or other portions of the system. As a result, it is feasible to produce reduced pressures within enclosed volumes. This can cause a collapse of vehicle tanks and of other types of ground storage tanks. Such occurrences have actually been recorded in the past. This hazard is therefore labeled greater for series than for parallel loading.

Tables 4f, 4g, and 4h present other assessments where differences in hazard between series and parallel loading were found. The rationale that were used to assess these differences were quite similar to those previously explained. As a general rule, the higher flow rates in the series operation would result in greater consequences of failure, if a failure in a given fluid system occurred without affecting the other fluid system. For example, if the series line bursts, more fluid could spill because of higher flow rates and larger line sizing. This would present a greater fire hazard potential. Additionally, the thermal shock potential of the higher spill rate would be greater in the series system.

Should a failure in one fluid system propagate a failure in the other (e.g., a LO_2 line ruptures and causes a LH_2 line to rupture), the consequence of the failure would be greater for the parallel loading system since both LO_2 and LH_2 systems would probably be operating at high flow rates when the failure occurs. Although this type of failure can occur in the series loading system, the resulting hazard would not be as great since both propellants would not be flowing at the time and therefore large quantities could not be mixed.

Table 4g. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
STRUCTURAL DAMAGE OR FAILURE (ANY PORTION OF THE SYSTEM SUBJECT TO ANY LOAD OR STRESS)	IMPACT OF DROPPED OR PROPELLED OBJECT	EXPLOSION AND/OR FIRE	A	S	S	G	S	S	L	TWO FLUIDS FLOWING
	MECHANICAL SHOCK AND FLUID HAMMER	LEAKAGE OF FLUID	C	S	G	S	S	L	S	LONGER EXPOSURE TIME
	EXPLOSION	SPILLAGE OF LIQUID CRYOGEN	A	S	L	L	S	G	G	FLOW RATES
	OVERLOADED AND/OR OVER-PRESSURIZED	BENDING AND DISTORTION LEADING TO FATIGUE FAILURE	B	S	S	S	S	S	S	
	FATIGUE FAILURE OF MATERIAL	STRESS CONCENTRATIONS AND CRACKING OF MATERIAL	B	S	S	S	S	S	S	
	STRESS CONCENTRATIONS	RUPTURE OF PRESSURE VESSEL, LINES OR OTHER COMPONENTS	A	S	L	L	S	G	G	FLOW RATES
	INADEQUATE DESIGN STRENGTH	CRUSHING OR COLLAPSING OF CONTAINER OR STRUCTURE	A	S	L	L	S	G	G	FLOW RATES
	FIRE AND HEAT DAMAGE	UNCONTROLLED FLUID FLOW	A	S	L	L	S	G	G	FLOW RATES
	IMPULSE AND MOMENTUM CONSIDERATIONS									
	CARELESS MAINTENANCE PRACTICE									
VIBRATIONS (MECHANICAL OR FLUID)	PUMPING OPERATION AND EFFECTS	FATIGUE OF MATERIAL	B	S	S	S	S	S	S	
	CHILLDOWN EFFECTS	LOOSENING OF MECHANICALLY CONNECTED COMPONENTS	B	S	S	S	S	S	S	
	CAVITATION	PRESSURE WAVES AND IMPULSE	B	S	L	L	S	G	G	FLOW RATES
	FLUID HAMMER	CHATTERING OF SPRING TYPE VALVES	C	S	S	S	S	S	S	
		FALSE READING OF INSTRUMENTATION	B	S	L	S	S	G	S	FLOW RATES
		FRACTURE OF BRITTLE MATERIAL	B	S	S	S	S	S	S	

A - CATASTROPHIC
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C - CONSEQUENCE CRITICALITY

G - GREATER
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Table 4h. Hazard Assessment

HAZARDS	POSSIBLE CAUSES	POSSIBLE EFFECTS	HAZARD ASSESSMENT GROSS	PARALLEL P	PARALLEL T	PARALLEL C	SERIES P	SERIES T	SERIES C	RATIONALE
WEATHER AND ENVIRONMENT	MOISTURE: RAIN, FOG, HAIL, SNOW	MOISTURE CONTAMINATION AND CONDENSATION	B	S	S	S	S	S	S	
(MAJOR PORTION OF SYSTEM LOCATED OUTSIDE)	TEMPERATURE EXTREMES	TEMPERATURE CYCLING OF SYSTEM	C	S	S	S	S	S	S	
	WIND	CORROSION	C	S	S	S	S	S	S	
	LIGHTNING	IMPACT DAMAGE FROM HAIL	C	S	S	S	S	S	S	
	AIRBORNE CONTAMINATION: DIRT, SALTS, AIR ITSELF AND ETC.	STRUCTURAL OVERLOADS FROM HIGH WINDS	C	S	S	S	S	S	S	
	SOLAR RADIATION	ENTRANCE OF CONTAMINATES INTO THE SYSTEM	B	S	S	S	S	S	S	
		LOSS OF ELECTRICAL POWER, POWER TRANSIENT, ELECTRICAL SHOCK, INADVERTANT ACTIVATION OF ELECTRICAL COMPONENTS.	B	S	L	S	S	G	S	FLOW RATES

A - CATASTROPHIC
B - CRITICAL
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D. - NEGLIGIBLE

P - PROBABILITY OF FAILURE
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C. HAZARD ASSESSMENT SUMMARY AND COMPENSATING PROVISIONS

Upon completion of the hazard assessment, those hazards where differences appeared between parallel and series loading were summarized in Table 5. (Where a hazard was assessed as greater, in either parallel or series, it has been indicated on the summary tables.) There were no cases where hazards appeared as greater under one of the classes of criticalities in both parallel and series. Therefore, it was possible to discontinue the distinction between the classes of hazards for the purpose of the summary sheets. The rationale indicated on the previous tables is repeated on the summary sheets for better visibility of the data.

The causes of the hazards were then evaluated to determine any compensation provisions that would be made. As an example, with reference to the hazard labeled "Acceleration" on Table 5, the possible effect of excessive pressure can be compensated for by controlling the time of opening and closing of valves to limit the amount of pressure surge. In the case of a structural failure for the same hazard, it is possible to compensate for the higher potential spill from a structural failure in the series system by providing isolation valves at strategic points in the lines. These valves can be closed in case of a failure, thereby limiting the amount of spill. For an explosion hazard, where a greater hazard exists in the parallel system due to the potential mixing of two fluids at high flow rates, compensation can also be achieved by providing barricades and retaining dikes, by preventing the crossing of lines containing the two different fluids, and by not running them adjacent to each other. Similar logic was used to arrive at all the compensating provisions shown in Table 5.

An evaluation of the 29 effects, where differences in criticality of the hazards between parallel and series appeared, showed that by providing the compensating provisions shown on Table 5, the hazards could be essentially equalized between the parallel and series methods. Incorporation of the compensating provisions would, however, increase the cost of the system thus negating the potential cost savings expected for a parallel system.

Table 5. Hazard Assessment Summary

Gross Hazard	Possible Effect	Hazard Rating: Gross	Parallel	Series	Rationale	Compensating Provision
Acceleration	Excessive Pressure	B		G	Higher Flow Rates	Controlled Flow
	Structural Failure	A		G	Higher Flow Rates	Isolation Valves
Contamination					No Significant Diff. Noted	
Corrosion						
Electrical	Loss Communication	B		G	Less Reaction Time	Redundancy & Backup
	Loss of Control	A	G			Fail Safe
Explosion	Structural Damage					
	Vehicle	A	G			
	PLS	A	G			Isolation Valves
	Shock Waves & Impulse	B	G			Isolation Valves
	Secondary Explosions	A	G			Isolation Valves
	Fragmentation Damage	A	G			Barricades
	Fire	A	G			Retaining Dikes

Table 5. Hazard Assessment Summary (Continued)

Gross Hazard	Possible Effect	Hazard Rating Gross	Hazard Rating Parallel	Hazard Rating Series	Rationale	Compensating Provision
	Injury to Personnel	B	G			Automatic Operation
Fire	Secondary Explosion	A	G			Retaining Dikes Isolation Valves
Heat & Temperature	Fire/Explosion	A	G		Two Fluid Flowing	Isolation Valves
Leakage					No Significant Diff. Noted	
Pressure	Component Rupture	B		G	Higher Flow Rates	Isolation Valves
	Explosion	A	G		Two Fluids Flowing	Isolation Valves
	Fragmentation	A	G		Two Fluids Flowing	Barricades
	Collapse of Pressure Vessel or Storage Tank	A		G	Higher Flow Rates	Precision Flow Control
	Fluid Hammer	B		G	Higher Flow Rates	Precision Flow Control
	Spillage of Fluids	B		G	Higher Flow Rates	Isolation Valves

Table 5. Hazard Assessment Summary (Continued)

Gross Hazard	Possible Effect	Hazard Rating Gross	Hazard Rating Parallel	Hazard Rating Series	Rationale	Compensating Provision
Shock	Structural Damage	B		G	Higher Flow Rates	Isolation Valves
	Fluid Hammer	B		G	Higher Flow Rates	Precision Flow Control
Stress Reversals	Fatigue Failure	A	G		Two Fluids Flowing	Isolation Valves
Structural Damage or Failure	Explosion/Fire	A	G		Two Fluids Flowing	Isolation Valves
	Spillage of Fluid	A		G	Higher Flow Rates	Isolation Valves
	Rupture of Pressure Containing Com-ponents	A		G	Higher Flow Rates	Isolation Valves Retaining Dikes
	Crushing or Col-lapsing of Container	A		G	Higher Flow Rates	Precision Flow Control
	Uncontrolled Fluid Flow	A		G	Higher Flow Rates	Isolation Valves
Vibrations	Pressure Waves	B		G	Higher Flow Rates	Precision Flow Control
	False Indicates from Instrumentation	B		G	Higher Flow Rates	Vibration Isolated
Weather and Environment	Loss of Electrical Power	B		G	Higher Flow Rates	Redundant & Backup Power Available

D. VEHICLE TANKAGE HAZARDS

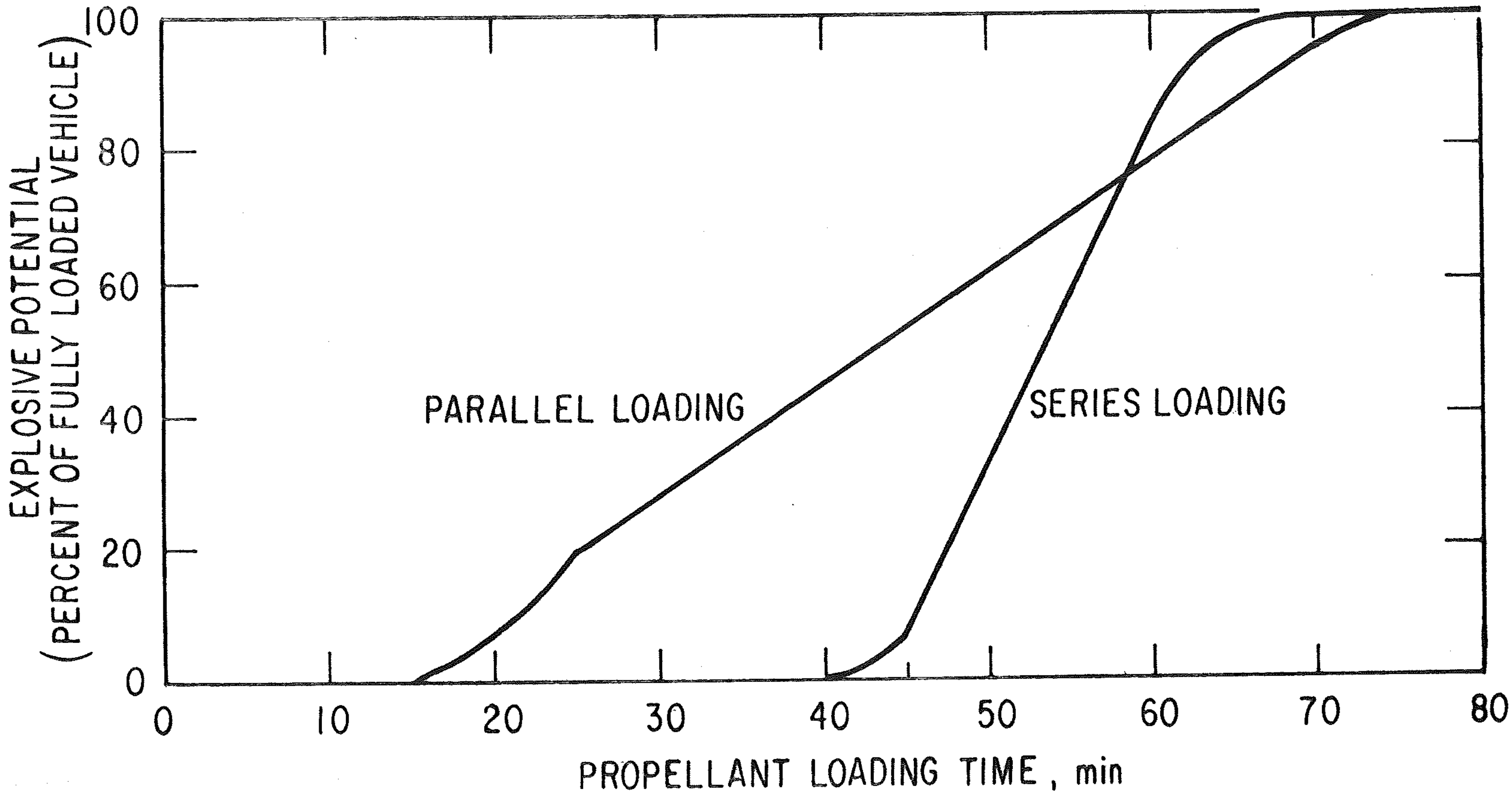
An investigation of the differential in hazard between the series and parallel loading methods was made based upon the degree of fullness of the vehicle tanks for each method.

1. Explosive Potential

Figures 2 and 3 graphically show the percent of total propellant loading within given periods of time for the series and parallel methods, respectively. The rates indicated on these figures were used to plot the explosive potential of the vehicle at various points in time during the propellant loading operations (See Fig. 8). The assumptions were made that an explosive hazard exists only when LH_2 is on board, and, when excess LO_2 is available, only the amount required for a stoichiometric reaction would be included.

Using these assumptions, the explosive potential of the fluids in the vehicle tanks during the series method of loading was evaluated. Since only the vapor from the small amount of LH_2 required to chill down the fuel tank is on board during the first 40 minutes of operation, zero explosive hazard is considered to exist during this time period. At 40 minutes, liquid LH_2 would start to fill the LH_2 vehicle tanks, and this amount of LH_2 could react with the LO_2 already loaded into the LO_2 vehicle tanks. The explosive potential of the mixture would rise in accordance with the rate shown on the curve in Fig. 8 due to the increasing amount of LH_2 that would be loaded into the tank.

For the parallel method of loading, a similar rationale was used. The explosive potential of the mixture of LH_2 and LO_2 would rise as indicated by the curve on Fig. 8. Since for the parallel loading method, LH_2 is loaded almost simultaneously into the tanks with the LO_2, the explosive potential would start to increase at an earlier time than the series method. This increase, however, would be at a slower rate.



ASSUMPTION:

1. EXPLOSIVE HAZARD EXISTS ONLY WHEN LH_2 IS ON-BOARD
2. WHEN EXCESS LO_2 IS AVAILABLE, ONLY THE AMOUNT REQUIRED FOR A STOICHIOMETRIC REACTION IS INCLUDED, I.E., 8 lb LO_2/1 lb LH_2

Fig. 8. Vehicle Explosive Hazard Versus Loading Time

In order to evaluate the overall difference in explosive potential between the parallel and series loading methods over the total propellant loading time, the area under the curves was calculated and used as an indication of which method presented the greatest explosive potential. It was assumed that launch would take place very soon after propellant loading. As indicated on Fig. 8, parallel loading resulted in an area under the curve of 53.1 explosive-potential-hr compared to 35.3 explosive-potential-hr for the series method. The indication, therefore, exists that parallel loading presents a greater overall explosive hazard from a standpoint of fluid contained in the vehicle tanks than the series loading method. It can be noted that by increasing the parallel loading rates, the time periods for parallel loading could be equalized with the series loading, and equal areas under the curves could be obtained.

2. Fire Hazard

An evaluation of the fire hazard presented by the fluid contained in the vehicle tanks was made and is shown in Fig. 9. The evaluation attempts to normalize the degree of fire hazard by expressing this hazard in terms of the heat released by burning of available combustible materials. It was assumed that during the time periods when LH_2 is not available, any LO_2 contained in the vehicle tanks could combine with the available metals as fuel for combustion; however, when LH_2 is available, the LO_2 would have a preference to combine with the LH_2, as opposed to metals. The heat releases shown in Fig. 9 are based on the propellant loading rates shown in Figs. 2 and 3 and the amounts of heat released if a fire loading would stop at the initiation of any fire.

In the case of series loading, only LO_2 is available during the first 40 minutes. Therefore, the potential heat release shown in Fig. 9 for series loading in the 10- to 40-min time period is the result of LO_2 combining with the vehicle structure. It will be noted that the heat release is a constant 60 percent in the approximately 20- to 40-min time period since sufficient LO_2 is on-board the vehicle after 20 minutes of loading time to entirely

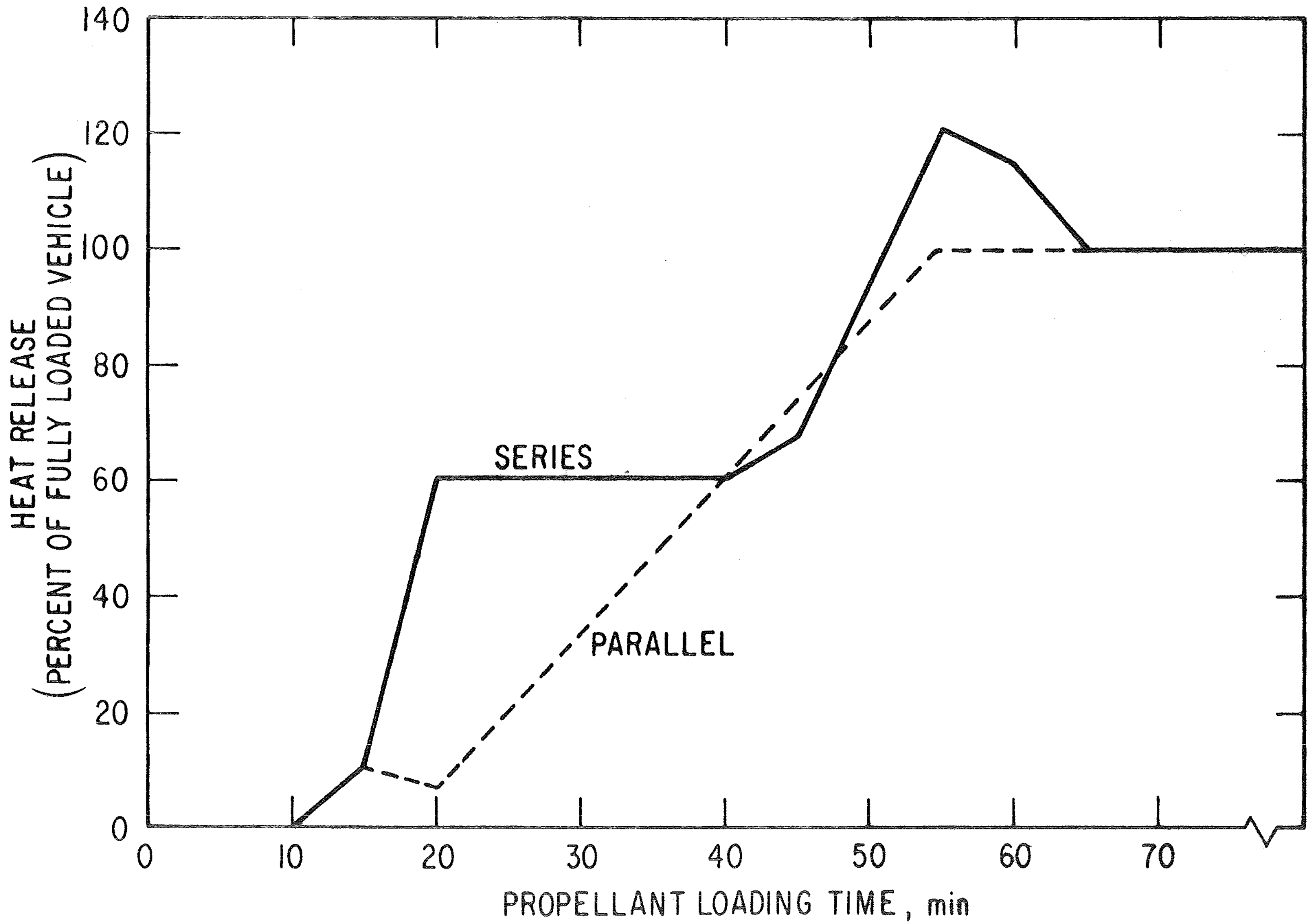


Fig. 9. Vehicle Fire Hazard Versus Loading Time

consume the vehicle. At 40 minutes into the series propellant loading sequence, LH_2 would start to enter the vehicle tanks and, should a fire occur after this time, LH_2, in addition to the vehicle materials, would be available for combustion. The addition of LH_2 as a fuel for combustion is reflected in the increased slope of the series heat release curve in the approximately 40- to 55-min time period with the maximum potential heat release occurring at 55 minutes. The heat release in the approximately 55- to 65-min time period reflects the combustion of the excess LO_2 (the LO_2 remaining after all the LH_2 is consumed) and the remaining vehicle materials. After approximately 65 minutes, the fire hazard, as expressed by potential heat release, becomes equal for both the series and parallel methods of propellant loading. The fire hazard for time periods beyond approximately 65 minutes can be considered as independent of the loading method used.

For the parallel method of loading, LO_2 and LH_2 are available for combustion in accordance with the assumption made that LO_2 has a preference for LH_2. The heat release as a result of the combustion of the two fluids is indicated with reference to the loading rates shown in Fig. 4.

The areas under the curves were calculated to indicate the relative amount of heat released using the two methods of loading. For the series loading, the heat release is 83 heat-release-hr as compared to 49 heat-release-hr for the parallel method. These values indicate a higher heat release (fire) hazard for the series method.

3. Drain Time

Drain time is utilized as an indicator of the relative safety of backout operations for the two methods of propellant loading. The relative time needed to drain the propellants from a fully loaded vehicle was evaluated using the fill and drain line sizes indicated in Figs. 4 and 6. Drain times will be less for the series loading method since, for equal loading time, the series method requires larger line sizes which will provide a greater drain rate capability. Based on the assumption that constant pressure in the vehicle propellant tanks is used to transfer the fluids from the vehicle into the storage tank, the relative drain time was calculated and is shown in Fig. 10. It can be seen that LH_2 can be drained in approximately 25 percent of the time, using the series line size, as compared to the parallel line size, and that the LO_2 can be drained in approximately 13 percent of the time, using the series line size, as compared to the parallel line size.

E. EFFECT OF VARYING LOADING TIME

While most of the previous observations were based on equal loading times of 75 min for the series and parallel methods of loading, some of the compensating provisions require a variation in loading time to obtain the compensations stated. The change in time is implicit in the lowering or raising of flow rates to reduce or equalize several of the hazards. Consequently, some comments are made pertaining to the effect of varying load times.

For the parallel loading method, the greater propellant loading system explosion potential can be reduced, but not completely equalized, by increasing the loading time. The greater vehicle explosion potential and backout time can be equalized by making the load rates approximately equal to the series method load rates. Since simultaneous flow of fluids takes place in the parallel method, this would decrease the loading time to approximately one-half the series time.

For the series loading method, the greater propellant loading system potential spillage, with resulting fire and thermal shock hazards, and the greater potential for structural damage can be equalized by decreasing flow rates. This would increase the loading time to approximately twice the parallel loading time. In contrast to this, the greater vehicle fire hazard can be equalized by increasing flow rates, so that less time is available for the combination of the LO_2 with the metal in the vehicle structure. This would thereby decrease the loading time.

A reduction of the parallel loading time to approximately one-half the series time would equalize rapid load rates between series and parallel and

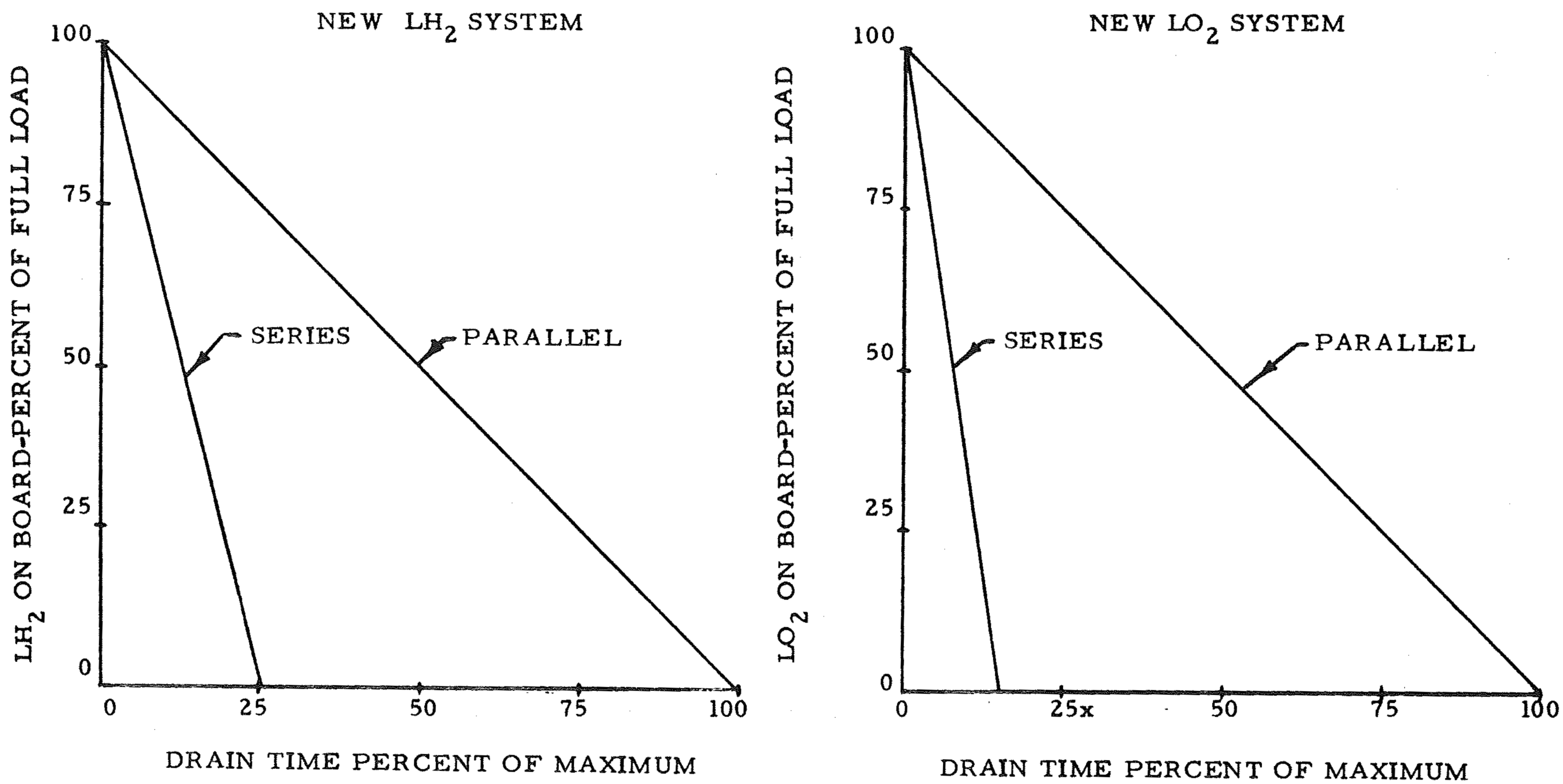


Fig. 10. Relative Propellant Drain Times
(Fully Loaded Vehicle)

would therefore require equal line sizes for both series and parallel methods. As a result, the explosive hazard of the fluids in the vehicle tank, the backout time, the propellant loading system line spillage, and the structural damage potentials would be equalized between the parallel and series methods. However, the explosion potential of the propellant loading system lines would be increased somewhat since simultaneous rapid flow of the two fluids at a higher rate would occur. The fire hazard due to the fluid stored in the vehicle tank would still be higher for the series method of operation, since LO_2 would be available for combustion with the materials in the vehicle structure.

V. SUMMARY

The results of the study on the relative hazards of parallel versus series loading of the Earth Orbit Shuttle (EOS) propellants are summarized in the following sections.

A. SERIES LOADING

The basic difference between the series and parallel methods of loading is that with the series method, approximately twice the flow rate would exist in each of the lines. If a failure in any one of the lines should occur, the potential for larger amounts of spillage would exist. This would create a greater hazard with respect to fire and thermal shock of surrounding structures. Additionally, the faster filling of the vehicle tanks also creates a potentially greater hazard relative to structural damage of components.

An assessment of the relative fire hazards of the two loading methods indicates that a higher hazard exists for the series loading method. The fire hazard was evaluated as a function of potential heat release in the event of a vehicle fire. Heat release is directly relatable to the LO_2 available to support combustion of the vehicle structural materials. A comparison of the loading methods presented in Figs. 2 and 3 will show that the series method provides larger quantities of LO_2 to support combustion earlier in the loading cycle than does the parallel method.

B. PARALLEL LOADING

The parallel loading method allows lower flows in both the LH_2 and LO_2 systems than the series method. However, if a failure in one of the systems should create a failure in the other system, the potential for mixing of the two fluids at rapid flow rates exists. This would create a greater explosion hazard than the series method of loading, where only one of these fluids is flowing at rapid rates at any one time. With respect to the fluids in the vehicle tanks, it was shown that a greater explosive potential exists for this method and that the backout time to drain vehicle tanks would be greater because of the smaller line size.

C. COMPENSATING PROVISIONS

With regard to compensating provisions to reduce or equalize the hazards between the two systems, the following comments are made.

1. Series Loading Compensation

Because of the potential for greater spillage, isolation valves can be installed at critical locations in the loading system. These isolation valves would allow shutoff where structural failures have occurred and could isolate that section. The higher pressure surges created by the higher series flows can be controlled by providing precision controls to regulate the greater valve closing or opening surges. The time period during which the vehicle is exposed to a greater fire hazard than during the parallel loading method is due to the availability of LO_2 to combine with the vehicle structure; it can be reduced, however, by increasing the LO_2 flow rate.

2. Parallel Loading Compensation

For the parallel method of loading, compensating provisions can be provided to reduce or avoid fluid mixing by providing barricades and dikes, eliminating the crossing of lines, and avoiding lines containing different fluids in close proximity to each other. The explosion potential due to fluid mixing as a result of structural failure of the propellant loading lines can be reduced by lowering the flow rates. The explosion potential of the fluid in the vehicle tanks can be equalized relative to the series method by raising the flow rates so that the fill rates of the parallel method of loading would equal that of the series method of loading. These higher flow rates necessary to decrease the explosion potential of the fluid in the vehicle tanks would require larger fill lines, thereby also providing an equalization of the drain time between parallel and series loading.

D. EFFECT OF VARYING LOADING TIMES SUMMARY

A reduction of the parallel loading time to approximately one-half the series loading time would equalize rapid load rates between series and parallel loading, and would, therefore, require equal line sizes for both series and parallel methods. As a result, the explosive hazard of the fluids in the vehicle tank, the backout time, the propellant loading system line spillage, and the structural damage potentials would be equalized between the parallel and the series method. However, the explosion potential of the propellant loading system lines would be increased somewhat since simultaneous rapid flow of the two fluids at a higher rate would occur. The fire hazard due to the fluid stored in the vehicle tank would still be higher for the series method of operation, since LO_2 would be available for combustion with the materials in the vehicle structure.

VI. CONCLUSIONS AND RECOMMENDATIONS

An evaluation of the overall hazards pertaining to the propellant loading of the space shuttle leads to the conclusion that for equal total loading times the parallel loading method is potentially more hazardous than the series method of loading.

It was shown that the reduction of parallel loading time to approximately one-half the series time would essentially equalize the differences in hazards between parallel and series. However, because equalization of loading time would require the same line size, valves, and other equipment as for the series system, the economic advantage of the parallel method of loading would be negated if this method were employed.

If it is assumed that only a relatively small percentage of missions will require a reaction time that necessitates loading propellants in 75 minutes, and that 150 minutes could be used for propellant loading for the majority of missions, then advantage can be taken of the smaller size and lower cost of the parallel method of loading. The system can be designed so that it would normally be operated in series, allowing approximately 150 minutes to load the vehicle tanks. For the vehicles that require the short reaction time of 75 minutes, the identical system which was sized for 150-minute series loading can be operated in parallel to load the vehicle in 75 minutes. In this manner, the smaller line sizes can be used, and the potential cost advantage of the parallel system as reported in Ref. 1 can be realized.

It is recommended that the hazards and compensation provisions noted in the hazard analysis be utilized to formulate system safety design criteria for the space shuttle propellant loading system.

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[*] An internal company document; not available for outside distribution.

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