LIQUID PROPELLANT LAUNCH VEHICLES FOR MANNED SPACE FLIGHT

by

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Introduction

Launch vehicle technology has probably been the most controversial aspect of the manned space flight program as it has developed during the past twelve months. This paper is a hopefully concise exposition of the present lunar flight system concept, and necessarily represents the concerted efforts of numerous individuals within government and industry who are engaged in the Apollo/Saturn program, and whose substantial contributions must be acknowledged at the outset.

In the midst of confusing and complex issues, we have seen through the year 1961 a period of resolution, reassessment and realignment of the national goals in space flight. This has been a period of great expectations, great impatience, intense debate, and concentrated technical effort. The decisions that have been made are emerging in broad outline in the contract structure. It is my purpose here to provide some insight into the assessment and decision phase that has led to our present position and course of action.

From the many conceivable lunar mission profiles, NASA has selected the rendezvous approach for the early Apollo manned lunar flights, based on the Saturn C-5 launch vehicle. Evaluation and selection of flight systems for lunar missions have proved a most intricate and demanding task. That which is technically feasible is not necessarily desirable in the broader sense of achieving a national objective. One must move far afield in systems engineering and operations research to associate mission concepts with the means of accomplishment for specific tasks within a given time frame. Selection of the present mode has been made in full recognition that we are stuck with these basic decisions for many years to come.

Lunar Flight Systems

The C-5 rendezvous approach for early manned lunar missions was identified and selected during the course of a series of in-house NASA studies that culminated in the recent NASA-DOD Golovin Committee. This concept has withstood the rigors of many months of critical examination. Although it has only recently been revealed as an integrated flight system, the various concepts consolidated in this plan existed in 1960, and in prior years.

Eventual full development of manned space flight requires a broad spectrum of mission capabilities extending from early spacecraft qualification flights in earth orbit through lunar logistics and planetary exploration. The principal flight systems considered for the lunar mission are indicated in FIG 1, along with mission phases.

Launch vehicles in three principal performance classes are required in sequence. The Saturn C-1 is aimed at a growth capability of 25,000 lb in earth orbit. The initial concept and objective of the booster was to demonstrate operational feasibility of clustered engine systems, to which has been added the development of large hydrogen-oxygen upper stage technology. Its principal mission in the manned space flight program is to develop the Apollo spacecraft. The second and larger vehicle, Saturn C-5, is aimed at initial manned lunar landing capability. The projected lunar orbit rendezvous mode provides approximately 90,000 lb to lunar transfer injection. The earth orbit rendezvous mode provides 400,000 lb assembled in earth orbit with a capability to inject approximately 150,000 lb to lunar transfer. The Saturn C-5 launch vehicle is utilized in qualification of the entire Apollo flight system, projected unmanned lunar logistics support, development of earth orbital operations technology, development of advanced nuclear propulsion technology, and the Apollo manned lunar circumnavigation and initial manned lunar landing. The Nova is generally conceived to be a direct mode vehicle, having a 400,000-lb earth orbit capability and a 150,000-lb injection capability to lunar transfer. Its applications include the Apollo lunar exploration phases following initial lunar landings, manned lunar logistics support of the lunar base, and development and application of both rendezvous and nuclear propulsion technology for initial planetary exploration.

In outlining such a program it is only natural to place reliance on the most accessible technology. Basic elements more or less in hand at the outset of this evaluation, which began in earnest one year ago, included the basic Saturn launch vehicle technology as we know it today, a substantial investment in the F-1 engine development, and a substantial investment in hydrogen-oxygen upper stage technology with the Centaur, the RL-10 engine, the Douglas S-IV stage, and the J-2 propulsion system development. At each step in the decision-making process, we have moved forward from an established position in launch vehicle technology.

To place events in perspective, consider the status of the national large launch vehicle program one year ago. FIG 2 shows the original Saturn building block concept in which the S-IV stage of C-1 moves to the third stage of C-2 and a new large hydrogen-oxygen stage known as S-II, powered by the J-2 propulsion system, is brought in to achieve maximum utilization of the 1.5 M lb thrust S-I stage. Indicated orbital capabilities for these systems were in the range of 20,000 lb for C-1 and 45,000 lb for C-2. The proposed prime mission for C-2 at this time was manned lunar circumnavigation with a forerunner of the Apollo spacecraft.

As illustrated in FIG 3, detailed conceptual design of the S-II stage was well underway with a 260-inch diameter and a propellant load of approximately 330,000 lb. Concurrently, the J-2 propulsion system was being developed, specifically

tailored to this stage concept.

Moving out from this base line into an evaluation of the lunar program, investigation of many alternate proposals in this performance class has shown conclusively that no newly conceived launch vehicle system would likely become available at a more rapid pace. The Saturn C-1 booster, as presently conceived, has moved on into the flight test phase. FIG 4 graphically depicts SA-1 at the instant of lift-off in its successful first-stage test flight in October 1961. The Saturn C-1, in its growth versions, is well on the way to becoming the "DC-3" of manned earth orbital space flight.

Evaluations of the lunar flight systems summarized in FIG 1 have indicated certain general fundamentals. It is clear that substantially larger flight systems are necessary; it is also substantially true that we cannot reach the moon without mastering liquid-hydrogen technology, regardless of booster configuration. This technology paces the program, and is in fact an awesome development as those familiar with it can readily testify.

Prime Approach

A very broad range of possibilities has been suggested for launch vehicle configurations to accomplish manned lunar missions. In establishing the present concept, all facets of advanced propulsion technology have been examined. The booster stage investigations range from all-liquid systems, through hybrid liquid-solid systems, to all-solid systems. Myriad combinations of high-energy upper stage systems have been utilized, each matched in its performance class to specific booster stages and mission profiles.

A starting point for establishing the concept is the projection of mission profiles such as lunar and earth orbit rendezvous, and the direct profile. Mission development projection establishes performance requirements, and determines the essential tasks for each mode and the flight sequence and number of flights to qualification. Conceptual design of approximately 50 launch vehicle systems was undertaken to match the performance requirements. The launch vehicle development projection then determines the flight sequence and number of flights for stage and vehicle systems qualification. The full mission model is then employed to integrate mission and vehicle qualification programs, to develop a master flight plan for each specific launch vehicle configuration, in which the expected flight history is projected on the basis of detailed failure modes analysis of the primary propulsion and related vehicle subsystems. With detailed PERT networks, operations analysis can proceed, incorporating manufacturing and test facilities, logistics, funding, schedules for engine stage and vehicle development, to assess the total system cost and capability on an operational basis in achieving the mission objective. Following initial screening of likely prospects, the assessment is recycled in greater depth in all areas of detailed preliminary design in the launch vehicle, and its primary subsystems, to establish technical feasibility and performance capability. In conjunction with operations analysis, the expected probability of mission success must be substantiated within expected funding levels and within the specified time frame. In successive iterations we move from the feasible to the desirable.

Many novel proposals offered to accomplish early manned lunar missions have not withstood critical examination. In development of the broad outline for projected lunar flight systems the contention is not primarily among launch vehicle concepts; it is between Nova class direct flight and C-5 class rendezvous modes. Studies indicate that whether we use liquid or solid booster stages is a relatively minor factor in achieving the desired performance capabilities. The large solid booster concept has been amply tested, and upon the most careful projections appears deficient as a prime approach. Its main attractiveness is contingent upon adoption of Nova concepts. If solid motor development and facilities concepts are aimed at growth capability for Nova class vehicles, the projected schedules for motor development and stage and vehicle integration become incompatible with lunar mission objectives in a C-5 class vehicle.

The Nova concept itself has also been amply tested. It has long been recognized that it is only the logistic support of a permanent manned lunar base, coupled with manned planetary exploration, that demands a booster of this capability. Only in view of a multibillion dollar national commitment for such a sustained and ambitious level of manned space flight activity does a decision to undertake Nova class booster development early make sense.

With rendezvous, the Saturn C-5 is large enough to do the initial mission; with all factors considered, it potentially provides the capability for the earliest manned lunar circumnavigation and manned lunar landing. The major advances in technology required for this concept are the development of hydrogen-oxygen systems and rendezvous techniques. This conclusion represents the end product of thousands of man-hours of homework and the integrated technical judgment of hundreds of individuals. Confidence in the validity of this approach is high.

The conceptual phases of the assessment and decision tasks have been concluded and implementation of the lunar flight program is well advanced, as indicated by the commitments represented in FIG 5. The Apollo spacecraft system is being developed by North American Aviation. The Saturn C-1, S-I stage is being developed by Chrysler Corporation Missile Division, and the S-IV stage by Douglas Aircraft Company. The Saturn C-5 is being designed and developed with Boeing on the S-IC stage, North American on the S-II stage, and Douglas on the S-IVB stage which also has application into Saturn C-1. The C-5 S-IC stage major assemblies will be fabricated at the newly acquired plant in Michoud, Louisiana; the S-II stage will be fabricated at Seal Beach; and the S-IV and S-IVB stages will be fabricated at contractor facilities on the West Coast. C-5 stages will be tested at MSFC, during the early phases of the program, and later at the newly acquired Mississippi Test Facility. The entire launch vehicle system will be flown from Cape Canaveral out of a newly acquired 80,000-acre site now being developed.

Evolution Of C-5 Concepts

Exposition of lunar mission profiles with the Saturn/Apollo flight system has been ably set forth in many previous papers and recent publications. The review of rendezvous modes herein is limited to those aspects of the flight system that reflect directly in launch vehicle systems engineering, which is approximately to the point of lunar transfer injection.

The present Saturn C-5 launch vehicle concept evolved in detail from conceptual design studies of the earlier Saturn C-4. Just as the Saturn C-1 program started with a well established H-1 engine program, the advanced Saturn concept starts with the F-1 engine depicted in FIG 6. This F-1 engine is expected to approximately equal in thrust the combined output of the eight H-1 engines of the present Saturn C-1 booster. Conceptual designs of a four-F-1 engine booster began at MSFC late in 1960, utilizing an expanded version of the four-J-2 engine S-II stage already in detailed preliminary design for the earlier C-2. This configuration was affectionally known as "Nova Junior" at the time, and evolved into the Saturn C-5 concept, shown in FIG 7, concurrently with the development of rendezvous concepts for the manned lunar mission.

It is important to note that this launch vehicle configuration is not optimized for a specific application. Rather it represents a careful balance of design choice decisions aimed at preserving mission flexibility throughout the range of applications in the rendezvous modes.

Rendezvous is largely a matter of staging technique and logistics in its effects on launch vehicle size and development phasing relative to the mission profile. The Saturn C-5 is capable of two general mission profiles based on rendezvous in lunar orbit and rendezvous in earth orbit. In earth orbit mode (EOR), rendezvous defers the commitment of men until flight readiness in orbit is verified; thus it is essentially a fail-safe technique. In lunar orbit mode (LOR) man is committed prior to rendezvous; thus a relatively higher degree of exposure is anticipated.

Rendezvous in earth orbit comes at a price in cost, complexity, and performance capability of the total launch vehicle system. A rather trite but fundamental equation can be stated as follows: 2 X C-5 is not equal to Nova. Depreciation to approximately 80 per cent of combined vehicle escape capability of 2 X C-5 results from the orbital mechanics and weight budgets associated with EOR.

In a very crude illustration, the logistics of earth orbit rendezvous can be summarized as follows: a plush manned lunar mission can be provided with a flight system based on ten F-1 engines. Now, this capability can be cut in a number of ways: one flight with ten F-1's (a Nova class vehicle), two flights with five F-1's, or five flights with two F-1's. Performance and cost optimization indicate the optimum solution to be two flights with five F-1's.

As it is presently conceived, the C-5 flight system has a flexible capability for lunar transfer injection payloads ranging from 90 to 150,000 lb, depending on the mode selected, and the time phasing in which the mission capability is required.

Two operating modes utilizing earth orbital operations with the Saturn C-5 are illustrated in FIG 8. In the tanking mode the tanker is parked in orbit with the full load of oxygen required for the orbital departure stage. The R-1 and R-2 stages plus the Apollo spacecraft system are mated and checked out on the ground, and launched as an integral unit by the second Saturn C-5 to the high departure orbit illustrated in FIG 9. Economics of the weight budget are such that the tanker represents a full load for one C-5, and the orbit launch vehicle with its LOX tank empty represents a full load for the second C-5. Following transfer of LOX from the tanker to the escape stage of the orbit launch vehicle, separation occurs at the designated station (FIG 8) in which case all equipment associated with rendezvous and propellant transfer are left behind in orbit. This arrangement has the obvious advantages of permitting staging to occur at lunar transfer injection so that the R-2 lunar braking and landing stage remains sealed until the lunar braking phase is initiated. This arrangement also provides the minimum orbital staytime for liquid hydrogen in the R-1 stage, and permits flexibility in loading because the liquid oxygen is most easily ballasted across the docking interface to equalize the launch load place on the two C-5 vehicles.

In the connecting mode, also illustrated in FIG 8, similar maneuvers are executed with the R-1 escape stage injected to orbit fully fueled. However, the staging ratio of the lunar transfer injection stage and the lunar braking and landing stage cannot be maintained as favorably. The injection maneuver has the disadvantage that the parasitic weight of the docking structure and auxiliary maneuvering propulsion systems must be carried part way to the transfer velocity, and the larger R-2 stage must provide a portion of the initial transfer injection. This stage thus arrives at the lunar braking maneuver with partially expended tanks and a used propulsion system having unpredictable leakage. In this mode an additional restart of the propulsion system is required on the braking and terminal stage, and the expected reliability deteriorates. Our present attention is focused on the tanking mode. The C-5 launch vehicle configurations employed in the tanking mode are illustrated in FIG 10. The C-5 launch vehicle configuration utilized here as a two-stage orbital carrier has an approximately equal payload for the unmanned first launch and the manned second launch.

As mentioned previously, the Saturn C-5 launch vehicle system is not an optimized system. The S-IC and S-II stages are basically designed for maximum orbital capability without sacrifice of the many other requirements placed on the design. Propellant optimization of the S-II stage is a compromise between the full five-engine burning case and the engine-out optimization. In the three-stage-escape configuration illustrated in FIG 7, design studies were undertaken specifically to assess constraints and compromises in stage configuration and vehicle performance associated with application of the "building block" S-IVB stage, which is utilized as an escape stage on C-5, an orbit launch stage for the tanking mode, and as a

second stage of the C-1 launch vehicle system. In all cases, designs were made for the maximum flight loads encountered in the limit loads case, e.g., the S-IVB when flown on Saturn C-1 is designed structurally to accommodate the three-stage-escape trajectory flight loads in the C-5 application. The S-II tankage is sized for the two-stage-orbit mission, and designed structurally for a three-stage-escape mission which imposes the highest aerodynamic and structural loads. The S-IC stage is designed substantially by ground windload and longitudinal accelerations, including the rebound dynamic loads in the tail section associated with approximately a three-second holddown during the F-1 engine ignition period. Alternate missions with the Saturn C-5 are flown off-loaded as required, with consequent performance deterioration. But with careful design choices, payload penalties can be limited to about one to three thousand lb in escape missions, which is acceptable in the interest of retaining mission flexibility without altering the basic stage geometries.

To summarize the C-5 applications, this launch vehicle is conceived as a flexible system to accomplish, in a two-stage orbit configuration, either of the earth orbit rendezvous modes illustrated; or in a three-stage escape configuration to accommodate the manned lunar orbit rendezvous mode as well as direct lunar logistics support; or in a two-stage escape configuration to accommodate the early Apollo lunar circumnavigation flights; or as a two-stage booster, to accommodate the NERVA nuclear third stage for escape missions; and to provide in the S-IVB a "building block" upper stage for the present Saturn S-I in the C-1 program.

To complete the picture of the Saturn C-5 as a basic launch vehicle, the booster stage, shown in FIG 11, will be approximately 140 feet long, 33 feet in diameter, and powered by five F-1 engines, using liquid oxygen and RP-1 fuel as propellants to deliver a sea level thrust of about 7,500,000 lb. The propellant containers will have a combined capacity of about 4,600,000 lb.

The basic propellant container design will feature a cylindrical structure that has separate bulkheads for the propellant containers, with the liquid oxygen tank forward and the RP-1 tank aft. Each container will have slosh suppression devices. The launcher holddown loads are distributed to the thrust structure by the launcher, or holddown, posts. Thrust loads introduced by the center engine are carried out to the ring frame of the thrust structure by a crossbeam system.

The four outboard engines are to be mounted on a diameter of 364 inches with an aerodynamic fairing located over each. Thrust loads are sheared out by four vertical posts over the engines. A separate liquid oxygen suction line, connecting each engine to the liquid oxygen container, will run through insulated tunnels in the fuel container. Two fuel suction lines connect each engine to the fuel container. Fuel container pressurization will be accomplished with helium. Gaseous oxygen generated in the engine mounted heat exchangers may be used for pressurizing the liquid oxygen tank; however, this scheme may be replaced by a helium system similar to that used by the fuel tanks, if weight and reliability advantages are realized. Engine gimbaling for flight control is accomplished by double-acting piston gimbal actuators using the RP-1 fuel, bled from the high pressure propellant feed system, as the hydraulic fluid. A staggered engine start and shutdown sequence is to be used.

The S-II stage, illustrated in FIG 12, will be approximately 80 feet long, 33 feet in diameter, and equipped with five J-2 rocket engines that operate on liquid oxygen and liquid hydrogen. The five engines will develop a total thrust of about 1,000,000 lb. Four of the engines will be mounted on a diameter of 210 inches, with the fifth engine mounted in the center of the conical thrust structure. The propellant containers will be designed for a capacity of about 900,000 lb.

The basic propellant tank structure is of a conventional semimonocoque design with a common, insulated, double walled bulkhead separating the liquid oxygen container from the liquid hydrogen container. The liquid hydrogen, as shown, is to be located above the liquid oxygen.

Control of the S-II stage will be achieved by gimbaling the four outboard engines. The center engine will be fixed. All five engines will be aligned parallel to the centerline of the vehicle.

The S-IVB stage employs similar technology to the S-II except for certain accommodations for adaptation to orbital launch operations. The propellant container design will be cylindrical with a diameter of 220 inches, with propellant capacity of approximately 230,000 lb. As in the S-II stage, a common insulated, double walled bulkhead will separate the propellant containers. The liquid hydrogen is above the liquid oxygen. This stage is conceived to be equipped with a single J-2 engine.

Operational Considerations

Returning again to the broad outline of projected lunar flight systems summarized in FIG 1, it has been shown that the principal dependence for the early manned lunar landing attempts is placed on the Saturn C-5/Apollo system. It appears likely that there will be substantial pressure to fly operationally early in the vehicle R&D program, which places a premium on the initial reliability growth history rather than the inherent or operational probability of mission success. The launched cost of these very large systems is indeed substantial and it is obvious that opportunities to fly will necessarily be limited by the available dollars, facilities, and launch crews. Also as vehicle capability moves into the 100-ton range, it is obvious that the investment committed in spacecraft systems and upper stages with each launch is tremendous even when a substantial portion of this weight is represented by propellants available in orbit.

The desire for high probability of mission success is evident. Very general statements have been made to the effect that "new design philosophy" must be adopted to achieve an order of magnitude increase in stage and subsystems reliability. Realistically, we are stuck with the technology rather as it exists today. The basic items of propulsion, structure and flight control that will be utilized in the first manned lunar

landing attempt are in hand. Figuratively speaking, the keel has been laid. In the area of propulsion, H-1 engine experience can be extrapolated but it is doubtful that this much experience can be gained on F-1 and J-2 engines prior to the point of commitment. Major portions of the engine system hardware, such as the F-1 prevalves, are being exercised on the test stands today, and vital items of this nature are not going to look much different when the C-5 first flies.

The flight history of past programs based on ballistic missile practice is hopefully not typical of expectations for the man-rated advanced flight systems utilized in the lunar landing program. Recent experience with Minuteman, Titan II, and Saturn C-1 offers encouragement that technology is improving more rapidly than the complexity of the flight systems. Holding on to these gains necessitates a rather conservative design philosophy for manned flight systems, leading hopefully to an inherently high tolerance for malfunctions, and a high confidence of early success. It is felt that the present Saturn C-5 concept represents a very substantial advance in launch vehicle technology that will stretch both our capabilities and our courage to accomplish. To place this development in perspective, FIG 13 presents a comparison of the present state-of-the-art in Mercury-Atlas with projections for Apollo flight systems. The intermediate launch vehicle is the Saturn C-1 configuration utilized for the Apollo earth orbital spacecraft qualification. The large model represents our present concept of the Saturn C-5. It appears that a substantial task lies ahead to achieve manned lunar landing within this decade.

LUNAR FLIGHT SYSTEMS

FIGURE 1

SATURN C-1

- EARTH ORBITAL LOGISTICS - GROWTH TO 25,000 POUNDS
- OPERATIONAL FEASIBILITY OF CLUSTERED ENGINE SYSTEMS
- DEVELOPMENT OF HYDROGEN OXYGEN STAGE TECHNOLOGY
- APOLLO EARTH ORBITAL SPACECRAFT QUALIFICATION FLIGHTS

SATURN C-5

- LOR MODE - 90,000 POUNDS TO LUNAR TRANSFER
- EOR MODE - 400,000 POUNDS ASSEMBLED IN EARTH ORBIT - 150,000 POUNDS TO LUNAR TRANSFER
- APOLLO FLIGHT SYSTEMS QUALIFICATION
- UNMANNED LUNAR LOGISTIC SUPPORT
- DEVELOPMENT OF ORBITAL OPERATIONS TECHNOLOGY
- DEVELOPMENT OF ADVANCED NUCLEAR PROPULSION TECHNOLOGY
- MANNED LUNAR CIRCUMNAVIGATION AND INITIAL MANNED LUNAR LANDING

NOVA

- DIRECT MODE - 400,000 POUNDS IN EARTH ORBIT - 150,000 POUNDS TO LUNAR TRANSFER
- APOLLO LUNAR EXPLORATION
- MANNED LUNAR LOGISTIC SUPPORT - LUNAR BASE
- DEVELOPMENT OF RENDEZVOUS AND NUCLEAR PROPULSION - PLANETARY EXPLORATION

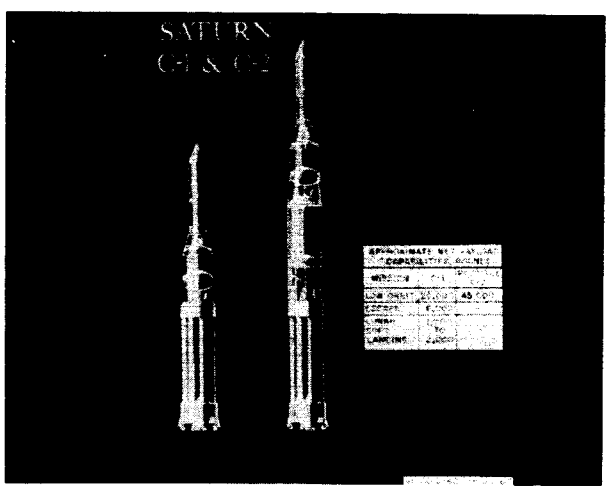

FIGURE 2

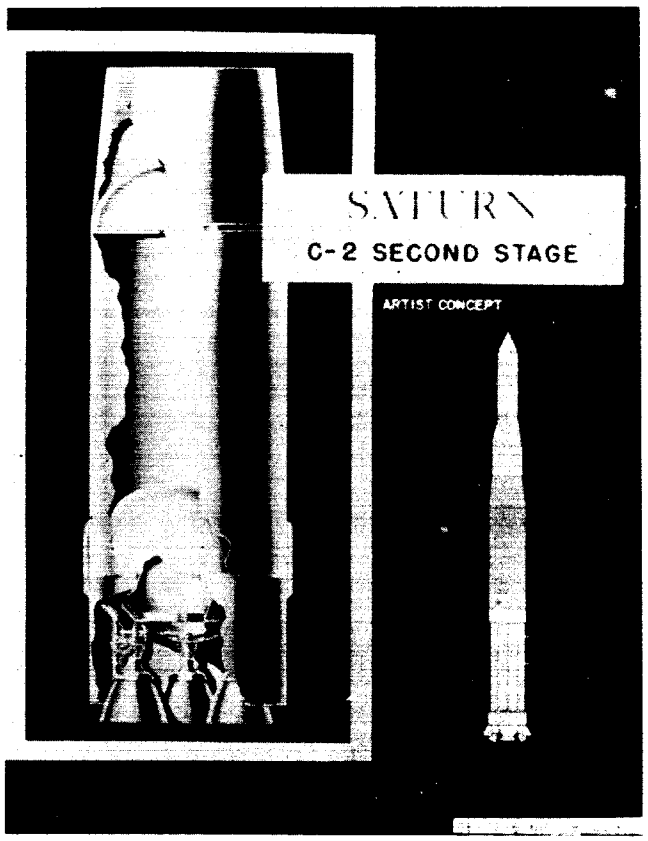

FIGURE 3

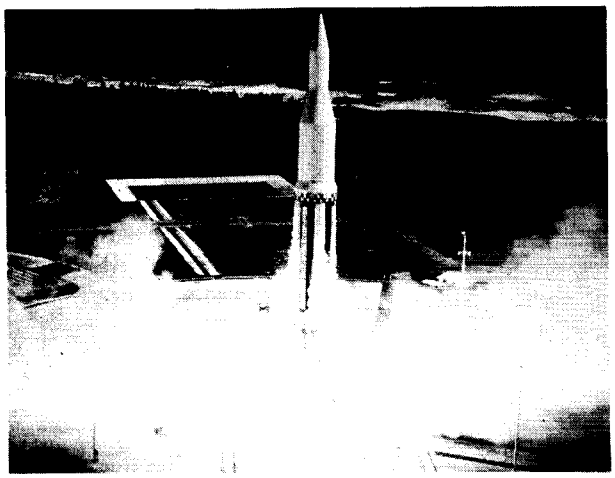

FIGURE 4 SA-1 AT INSTANT OF LIFT-OFF

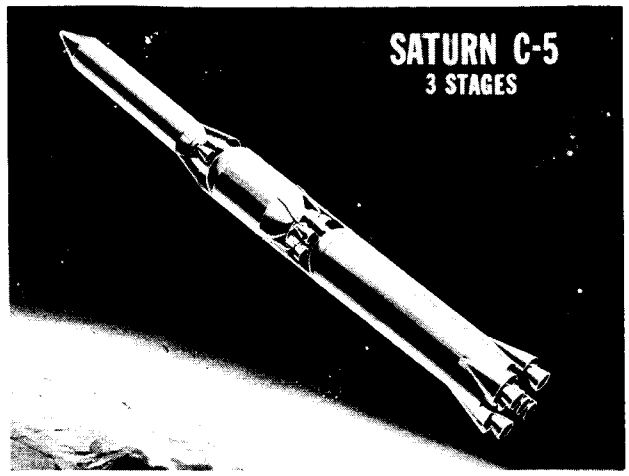

FIGURE 7

FLIGHT SYSTEMS
IMPLEMENTATION

- SPACECRAFT SYSTEMS
  APOLLO - NORTH AMERICAN
  GEMINI - McDONNELL
- BASIC PROPULSION
  H-1 F-1 J-2 ROCKETDYNE
  RL10 PRATT AND WHITNEY
- LAUNCH VEHICLE SYSTEMS

SATURN C-1

S-1 STAGE DEVELOPMENT - CHRYSLER/MSFC
S-IV STAGE DEVELOPMENT - DOUGLAS

SATURN C-5

DESIGNED AND DEVELOPED

S-IC STAGE - BOEING
S-II STAGE - NORTH AMERICAN
S-IVB STAGE - DOUGLAS

FABRICATED
MICHOUD
SEAL BEACH
WEST COAST FACILITIES

TESTED
MSFC
MISSISSIPPI TEST FACILITY
WEST COAST FACILITIES

LAUNCHED
AMR - CAPE CANAVERAL
80,000 ACRES

M-1 ENGINE - AEROJET

FIGURE 5

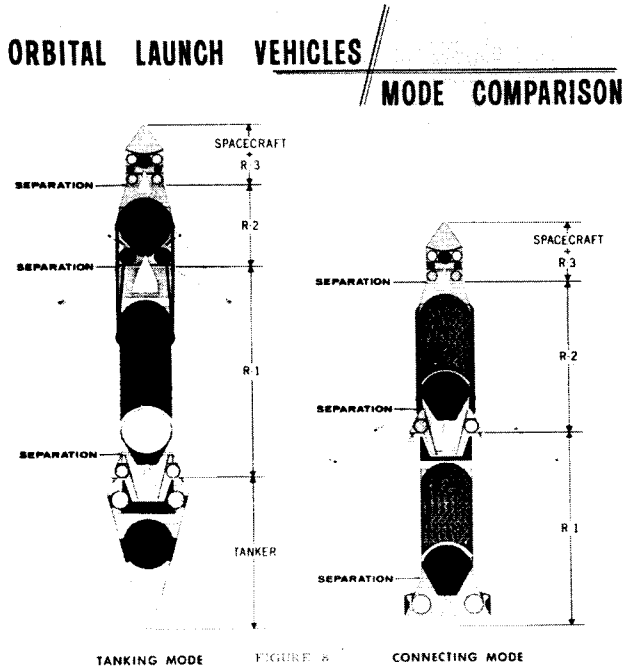

FIGURE 8

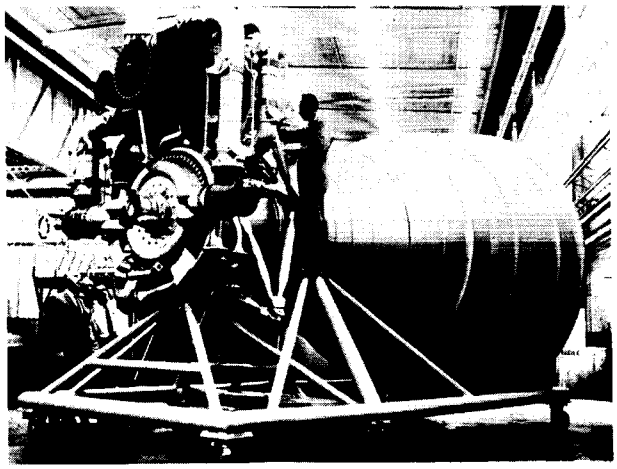

FIGURE 6 F-1 ENGINE

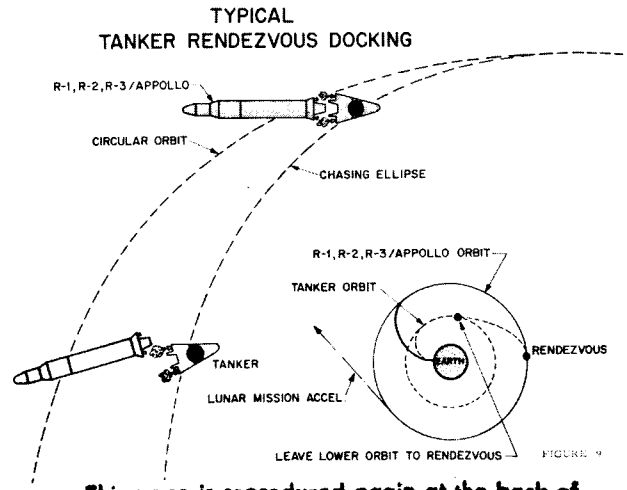

FIGURE 9

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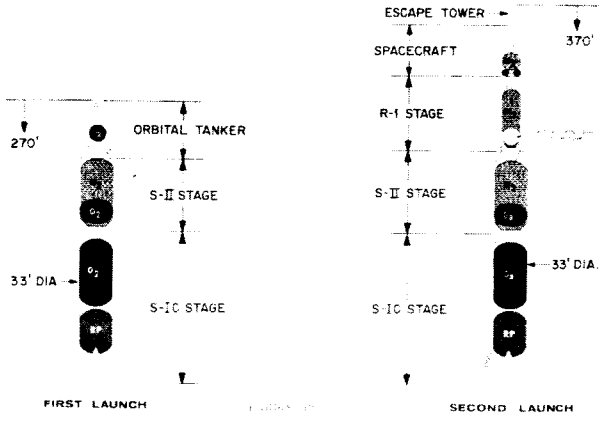
(TYPICAL) C-5 FOR ORBITAL OPERATIONS
TANKING MODE



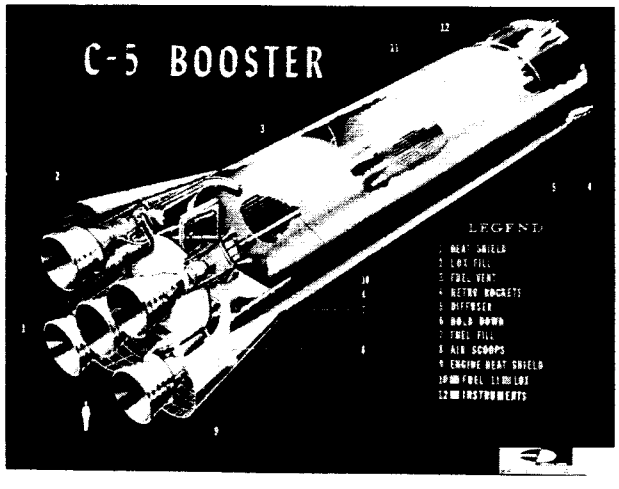


FIGURE 11

S-II STAGE

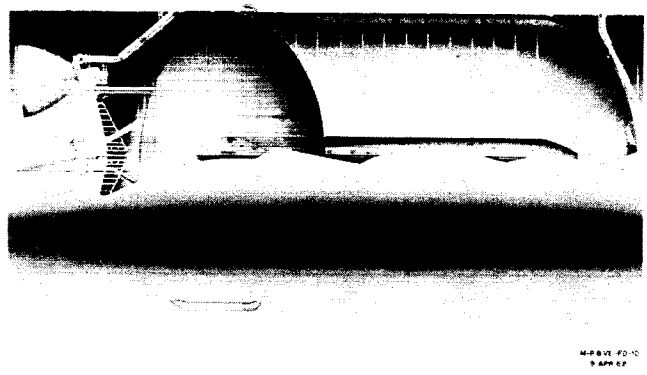


FIGURE 12

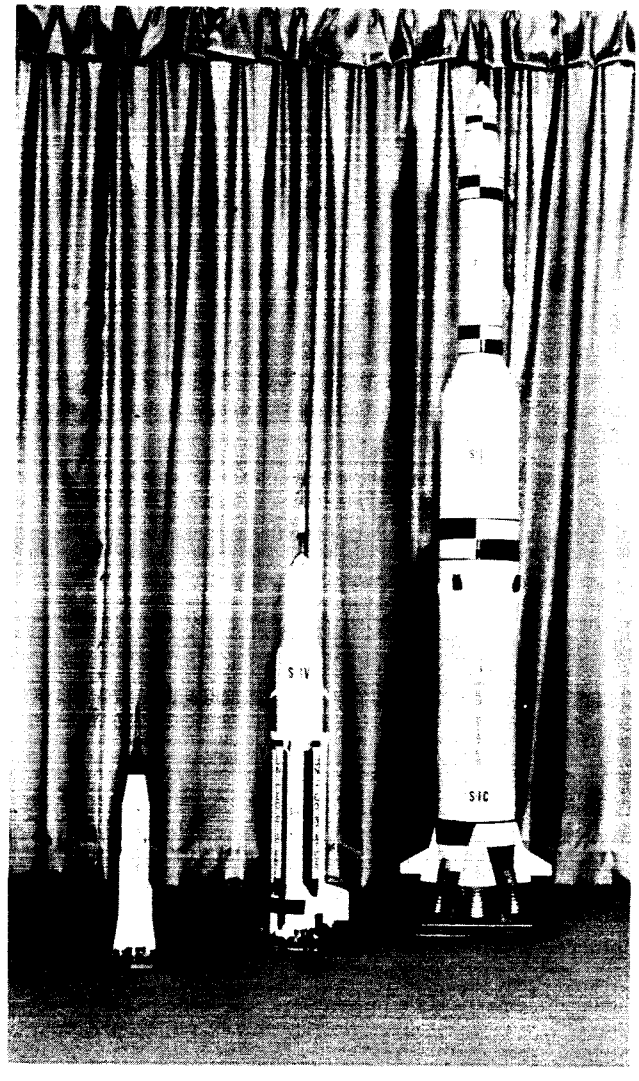


FIGURE 13 COMPARISON OF THE PRESENT STATE-OF-THE-ART IN MERCURY-ATLAS