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Apollo Lunar Orbit Rendezvous Architecture Decision Revisited

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The 1962 Apollo architecture mode decision process was revisited with modern analysis and systems engineering tools to determine the key selection criteria and technology/operational mode design decisions that may be used for NASA's current Space Exploration program. Of the four architecture modes that were finally considered for Apollo, the present study results agreed with the 1962 selection of the Lunar Orbit Rendezvous mode based on the technology maturity and politics at that time. Using today's greater emphasis on human safety and improvements in technology and design maturity, a slight edge may be given to the direct lunar mode over lunar orbit rendezvous. Reliability and development, operations, and production costs are major drivers in today's decision process.

I. Introduction

IN 1962, NASA established a systems analysis group at NASA Headquarters to compare the competing concepts for lunar exploration based on 1) the early successful landing of manned spacecraft on the moon and safe return to Earth (President Kennedy's criteria), 2) the support of future manned scientific missions, 3) the utilization for advanced military missions, and 4) the reliability and economic improvement through the reuse of vehicle components, vehicle stages, and complete launch vehicles [1]. This group eventually focused on four separate concepts [2] that were advocated by the Marshall Space Flight Center, Manned Space Center (Johnson Space Center), Jet Propulsion Lab, and Langley Research Center as explained later in the paper. Decision criteria established for operational mode selection by this group included performance (weight, margin, and sensitivity), probability of success of the first flight, time to first successful landing, probability of crew lost on the first attempt, research and development cost, operational cost of the first success, number of personnel at the lunar base, and man–year average cost. Based on this study, a minimum set of conceptual analysis tools are required for trajectory performance, weights, reliability, stochastic scheduling (if schedule date is dictated), research and development cost, and operations cost.

This paper revisits the Apollo decision process using modern engineering analysis and systems engineering tools. Two perspectives were taken in this study, a historical perspective of what was driving the decisions in 1962 (schedule, technology uncertainty, and cost) and today's driving perspective (human safety, emphasized cost, and sustainability). In addition to conducting the engineering trade studies of the four architecture modes, modern multi-attribute decision analysis is used to identify the driving decision criteria then and now which was not used for the Apollo decision. These driving selection criteria will focus the development of improved engineering analysis tools in order to arrive at a better architecture selection. Finally, various propulsion technologies are infused into the architectures to identify key technology drivers in the design decisions for NASA's Space Exploration program.

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II. Architecture Modes

The four lunar architecture modes that NASA was considering in 1962 were lunar orbit rendezvous (LOR), Earth orbit rendezvous (EOR), Liquid Nova direct flight (Nova DF), and Saturn C-5 direct flight (C-5 DF) as described in [3]. Figures 1–3 illustrate the concept of operations for each of the modes.

The LOR mode requires one launch on the Saturn C-5 vehicle, whose Saturn V upper stage (S-IVB) doubles as the translunar injection stage (TLIS). The command service module (CSM), which consists of the manned return and entry module, called the command module (CM), and the lunar capture/trans-Earth injection module, called the service module (SM), separates from the stack while on the translunar trajectory to reorient and dock with the lunar excursion module (LEM) for lunar descent and ascent. The CSM, while docked to the LEM, performs a propulsive capture to attain low lunar orbit (LLO). Two of the three crew members transfer to the LEM and begin their powered decent and landing on the lunar surface. After the lunar mission is complete, the two crew members launch from the lunar surface using the lunar ascent module (LAM); the lunar descent module (LDM) is staged off and left on the lunar surface. The LAM enters into an intercept trajectory to rendezvous and dock (thus lunar orbit rendezvous) with the remaining crew member in the orbiting CSM. After transferring back to the CSM, the LAM is jettisoned and the CSM performs a trans-Earth injection (TEI) for direct reentry into the Earth's atmosphere. The command module (CM) then separates from the service module (SM), reenters the atmosphere, and splashes down in the ocean.

The EOR mode requires two launches on the Saturn C-5 vehicle as shown in Fig. 2. The first launch does not use the S-IVB upper stage of the C-5 vehicle. Instead, the first two stages of the C-5 vehicle are used to deliver an unmanned tanker vehicle that contains the required oxidizer for the translunar injection (TLI) burn. The tanker waits in low-earth orbit (LEO) until the second launch. The second launch payload is the CM, SM, lunar touchdown module (LTDM), lunar braking module (LBM), and TLIS from top of the stack to bottom. The TLIS is similar to the S-IVB upper stage. The TLIS arrives in low-Earth orbit with the required fuel for the TLI but needs to be resupplied with LOX from the tanker. After LOX transfer, the tanker separates, and the TLIS performs the TLI. In the vicinity of the moon, the LBM begins a retro burn to slow the stack on its approach. The LBM is staged; without entering LLO, the LTDM performs the powered descent and landing on the lunar surface. At the end of the lunar surface stay, the CSM launches from the lunar surface and performs the TEI maneuver for direct Earth reentry, leaving the LTDM on the lunar surface. Near the Earth, the CM separates from the SM and reenters for splashdown.

The two direct flight options, Fig. 3, Nova DF, and C-5 DF, entail the same maneuvers with different size and capability launch vehicles. The Saturn C-5 launcher had a significantly smaller payload capability than the Liquid Nova launcher; this requires that the CSM be scaled down from a 154 in diameter to 138 in. The direct

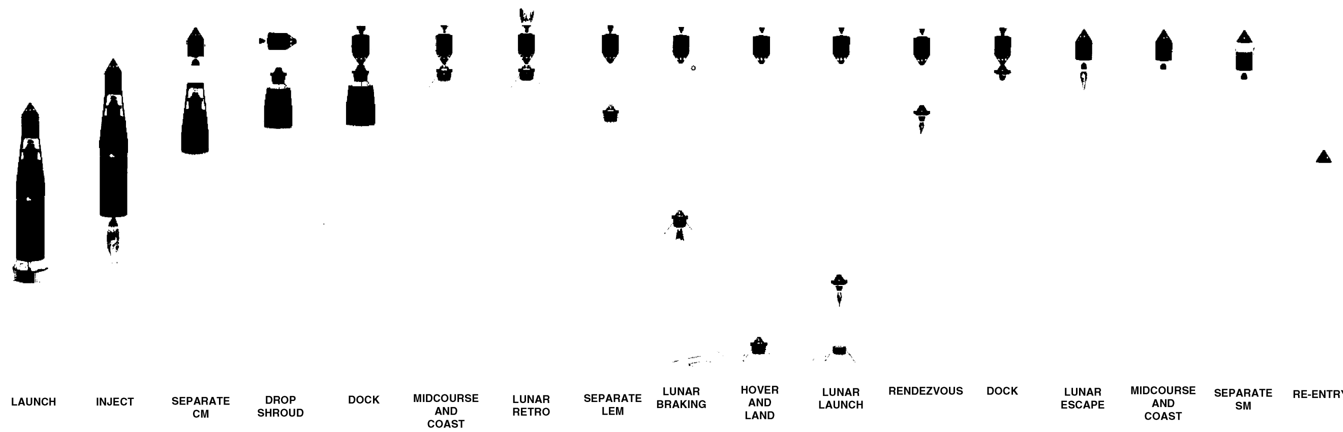

Fig. 1 Lunar orbit rendezvous concept of operations [3].

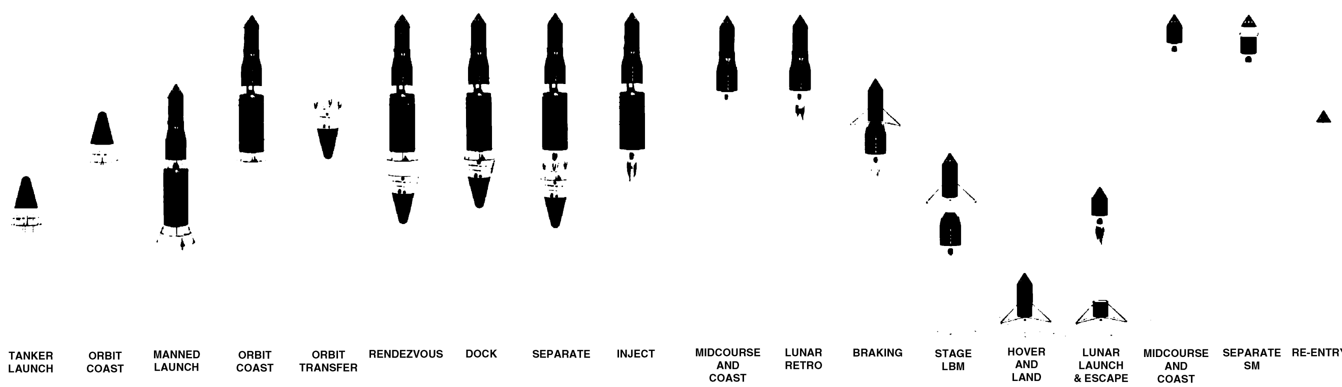

Fig. 2 Earth orbit rendezvous concept of operations [3].

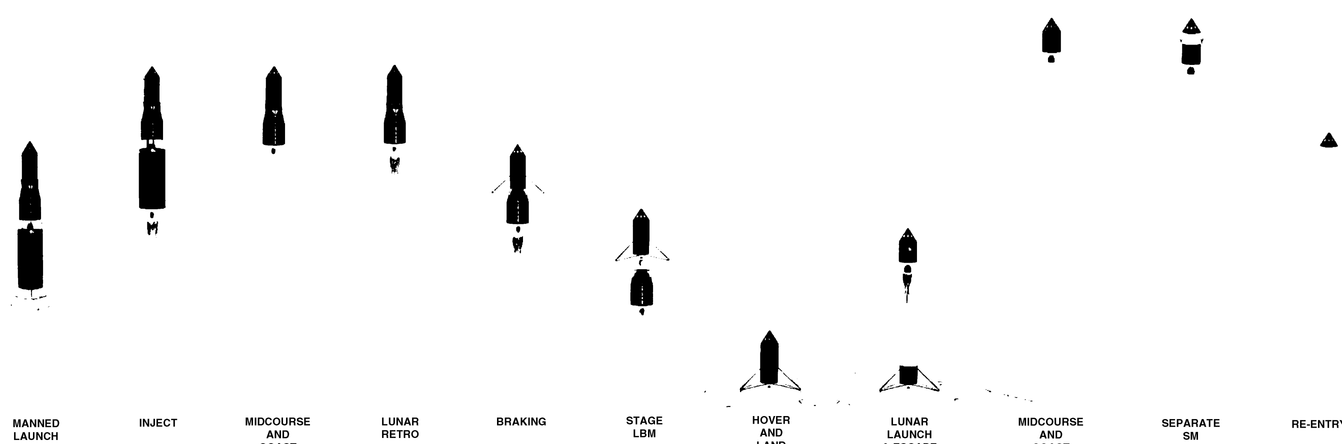

Fig. 3 Direct flight concept of operations [3].

flight modes require one launch on the Liquid Nova launch vehicle or Saturn C-5 launch vehicle, respectively. After launch, the two modes are very similar to each other and to the EOR mode; the only difference is the mass and size of the hardware and there is no need for propellant transfer. After insertion into LEO, the TLIS performs the TLI maneuver, pushing the CM, SM, LTDM, and LBM towards the moon. The remainder of the mission follows the EOR mission directly.

III. Analysis

A. General Approach

The four architecture modes studied in 1962 for Apollo differed in their operational architecture, physical architecture, propellant systems, size, mission duration, and crew size so that each could be optimal for the assumptions in the architecture. Thus, a direct comparison of the architectures from the Apollo study was very difficult. In this study, these modes were modeled exactly as they were described in [2,3] for performance, mass, cost, reliability, and system sensitivity for analysis validation. However, to achieve a direct comparison, all architectures were set to the specifications used by the original LOR mode. These changes included setting the command and service modules to a 154 in. diameter and using hypergolic propellants on the service and lunar modules instead of cryogenic propulsion. This gave an “apples to apples” view of how these systems stacked up to one another.

The design space was further widened by analyzing cryogenic systems that used liquid oxygen with either liquid hydrogen

(LOX/LH2) or methane (LOX/CH4) on the service and lunar modules. The TLISs were still assumed to be the S-IVB upper stage, or some derivative, and therefore used a LOX/LH2 system for all modes. The braking stages were also assumed to use a LOX/LH2 system in order to achieve highest in-space performance. All four modes were updated to be compatible with each propellant type and a full mass, cost, reliability, and sensitivity study was completed on each. This resulted in 16 distinct architecture modes that were carried out through the rest of the study.

B. 1960s vs Modern Objectives

Although there are many similarities between the vehicles that are being designed for the lunar mission today and those used in the Apollo program, the objectives for traveling to the Moon are vastly different. When making a final mode selection these differences can have a substantial effect. As will be shown later, throughout this study all analysis and selection was repeated twice using these two different mind-sets. When defining the 1960s mentality, [3] was used to determine a thought process close to that of the original decision makers in 1962. This included having a limited knowledge of space transfers, rendezvous and dockings, and the lunar surface. For these reasons as well as the political environment of time, the programmatic sensitivities and development risk were the two largest factors.

President Kennedy set a rigid timeline that had to be met. This was a difficult challenge due to the large number of immature technologies that could quickly become impossible to develop within the allotted time. President Kennedy also stipulated that a man must not only land on the moon but return safely. Uncertainty was already a large part of the design process, but in order to ensure the safest possible flight, reliability of all systems needed to be maximized wherever possible. Cost and therefore sustainability were of least importance. As a political challenge the space race needed to be won, and the President was willing to spend money to do so. The United States was only concerned with being the first to the lunar surface even if the missions were expensive and only a few could be flown.

Today there is no space race, and the president is calling for the United States to demonstrate its lead in science, research, and exploration, not just brute strength. Thus, the new mission must be able to perform much more research on the surface as well as provide for a much longer surface stay. NASA now has much more experience with manned spacecraft and in-space trajectories and maneuvers. Newer tools, knowledge of past growth, and existing equipment also allow the modes to be defined with much less uncertainty. Combined with President Bush's loose timeline, this greatly reduces the importance of programmatic sensitivities and development risk. The public perception of the importance of the space program and the importance of an astronaut's life has also changed. After the Columbia tragedy, NASA cannot afford another failure, especially if it leads to loss of life, in today's critical society. Therefore, reliability is a major concern.

Perhaps the biggest change from a design aspect is that the system must be sustainable, which translates most directly to operations cost. NASA is now on a very tight and uncertain budget. This new program must not only be developed under the current restrictive budget, but be able to be maintained under a budget that is yet to be set and could be possibly be cut even further.

C. Figures of Merit

After analyzing the two thought processes for operational mode selection, a list of six figures of merit (FOMs) that could adequately rate each mode as well as relate to the objectives of the mission were developed. One aspect important to each mind-set was reliability. To get the most variation as well as a qualitative assessment, reliability was defined to be the likelihood of any failure, critical or otherwise.

Cost was separated into three categories: production, operations, and design, development, testing, and evaluation (DDT&E). Production cost was defined as the cost to manufacture all hardware for one mission. This included all in-space elements as well as launch vehicles. Operations cost is the cost to operate a single mission, which included launch preparations, command center time, and facility maintenance. All expenses before and including the production of the first complete fight system was incorporated into DDT&E cost. Production and DDT&E costs were calculated and assessed quantitatively through the NASA/Air Force Costing Model (NAFCoM) as described later while operations cost was assessed qualitatively based on the number of launches and complexity of the systems and required maneuvers.

Development risk took into account the number and complexity of critical technologies that need to be developed for each mode. This was weighed against the time this development would take, the timeframe given, and its flexibility. Programmatic sensitivity is a measure of the interdependence of all elements of each mode; it shows the effect on the entire system when one element is changed. It was assessed comparing the architecture masses after adding a 10% growth to the inert weight of each element to the total architecture masses without any growth. Lower sensitivities potentially decrease the development risk on all systems that are affected by size and mass growth.

D. Multi-Attribute Decision Making

The "best" architecture mode was determined using a multi-attribute decision making (MADM) process using the FOMs and weights shown in Table 1. The relative importance of the FOMs was calculated using the analytical hierarchy process (AHP) using the authors of this paper as the decision experts; thus to eliminate author bias, sensitivity analyses were conducted to determine the changes in architecture rankings with the uncertainty of the weights. As described by Saaty [4], AHP uses a full factorial user-defined pairwise comparison to numerically determine a normalized importance for each FOM. In the process, AHP calculates a consistency ratio, which is used to ensure that the comparisons are consistent with each other, to eliminate bias, and to ensure there were no errors when filling out the inputs. The weightings for each FOM and mentality are listed in Table 1. The resulting weights were then fed into the technique for order preference by similarity to the ideal solution (TOPSIS) to rank each of the modes with respect to the FOMs. Kirby [5] explains that TOPSIS incorporates a user-defined decision matrix that compares each alternative to the baseline using a number scale from 1 to 9 with 5 being the same, 9 being much better, and 1 being much worse. This matrix was populated using

Table 1 Descriptions and weighting scenarios of the figures of merit

FOM	Description	1960s weights	Present weights
Production cost	Cost per mission of manufacturing all required architecture elements	4%	13%
Reliability	Probability of a hardware failure, critical or otherwise	21%	33%
Operations cost	All costs per mission not including production	7%	33%
Development risk	Probability that the technology required one or more of the elements will not be fully developed in the desired timeframe	21%	3%
DDT&E cost	Cost to design, develop, test, and evaluate all architecture systems to the initial operating capability date	4%	13%
Programmatic sensitivities	Risk associate with the sensitivity of each element of the architecture to the other elements	43%	5%

normalized data from the mass sizing, costing analysis, reliability calculations, sensitivity studies, and qualitative engineering assessment where no hard data was available. TOPSIS then formulates a "most ideal" and "least ideal" solution. Their Euclidean distance from these "ideals" ranks the alternatives. This entire process was carried out with both a 1960s and modern approach.

E. Analysis Tools

Vehicle masses were calculated using one of two tools. To model all service, command, and lunar modules, an Excel-based program designed to model Apollo and Apollo-like systems was used. This program is based on mass estimating relationships correlated to historical Apollo data from Heineman [6]. Inputs include engineering parameters from the number of crew to mission duration and cover a wide range of system parameters that are known during the initial design phase. This program sizes the system to meet payload requirements. All modes were assumed to have the same technology using comparable hardware to that which was used by Apollo.

The TLIS, LBM, and tanker were sized using the space propulsion sizing program (SPSP) [7]. The SPSP uses a combination of historical data, mass estimating relationships, and bottoms-up, physics-based calculations to design in-space propulsion stages on a system-by-system basis. It has been benchmarked against flown hardware and stages, including the Centaur upper stage, Delta IV upper stage, and S-IVB upper stage. In addition to the main SPSP, the tanker version SPSP-T was used to size the tanker for the EOR modes. These programs were developed within the Architectures, Missions, and Science Branch at NASA Langley Research Center.

Using the Excel-based program [8], the reliability of 39 components, systems, and maneuvers can be determined. Some of the components are batteries, fuel cells, tanks, and displays. Some of the systems described are the propulsion system, electrical system, and communications. The maneuvers covered are rendezvous, docking, and separation. By selecting the applicable components, determining whether reliability is based on cumulative hours or cycles, and indicating the level of redundancy, the program provides the module's reliability. The product of all of the module reliabilities in the mission yields the system reliability. This output is the probability of any failure of the system, and it does not make any assumptions about critical or fatal failures. The primary assumption for using this program stems from the duration or number of cycles a component is used. For example, any cryogenic tank reliabilities are based on the duration in which the engines are fired. This analysis inherently assumes perfect reliability during dormant phases of the mission.

The cost for each element was estimated using the NAFCoM [9]. The NAFCoM software allows the user to cost a project primarily based upon mass and required technology development. An element's cost is evaluated using the mass, performance, technology readiness level, and assumed type of management, design maturity, and funding stability for each subsystem of the element. For a conservative cost estimate, it was assumed that each system was a new design with the worst possible management. This was done for each of the elements modeled in the NAFCoM. The NAFCoM was benchmarked versus the Apollo program for each of its modules and was within approximately 15% of the actual cost.

IV. 1960s Decision

A. Selection Process

The TOPSIS results for the four architecture modes evaluated in 1962 are shown in Fig. 4. The plot shows the rank of the modes for each FOM. For example, under development risk, the rank from highest to lowest is LOR, C-5 DF, Nova DF, and EOR where the Nova DF and EOR have similar scores in that category. A first estimate for the best of the four modes is the one corresponding to the line that occupies the most area on the plot. This is an incomplete view of the TOPSIS results since the relative weightings of the FOMs must also be considered. The final result of TOPSIS for each mode using the 1962 mentality is shown in Table 2. The most ideal option receives a score close to 1, and the least ideal option receives a score close to zero. Since TOPSIS provides a relative assessment, if an option scores lowest in each of the FOMs, it will have a score of zero; this is seen in the EOR scores for the 1962 and apples to apples modes. The analysis indicates that LOR is a superior option over the other three modes. This complete ranking, using modern systems engineering techniques and approaches, is consistent with the ranking found in 1962.

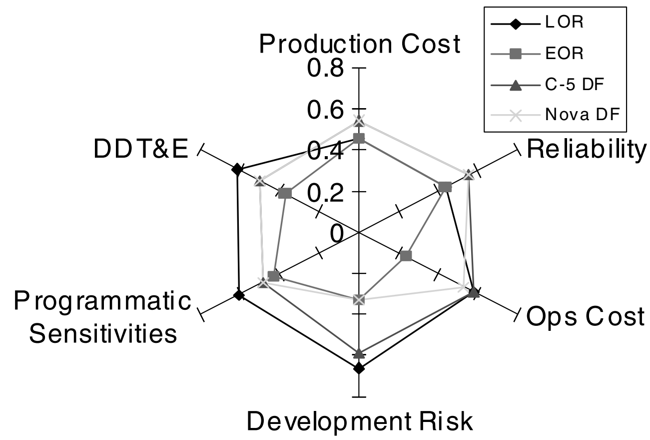

Fig. 4 Apollo operational mode comparisons.

The decision made in 1962 was based on similar analysis. However, one of the objectives at that time was to rule out any mode that was technically infeasible. The conclusion of the original study was that with the right amount of time and money any of the four modes could be used to land on the moon [1,3]. Unfortunately, at the time of the mode comparisons, there had already been several contracts signed for development of key Apollo systems, including the CM, SM, and parts of the Saturn C-5 launch vehicle. Since time was limited by the approach of the end of the decade, a mode needed to be technically sound and make the most use the hardware already under contract.

The Nova DF mode was found to be the least complex, safest, and required the fewest technology advances. It did, however, require the development of a much larger launch vehicle than that of the Saturn C-5, already under development. This pushed its schedule such that the first attempt at a manned lunar landing would be after the end of the decade, making it an undesirable option.

The C-5 DF mode required the use of high-energy cryogenic propellants in both the lunar landing and return stages. The complex propulsion system, despite its high performance, allowed for the least margin, based on the growth sensitivities when 10% mass was added to the inert architecture masses. Additionally, this mode required a much smaller CM than that under development, providing a minimal working environment for the crew. Combined with the high sensitivity to growth, the C-5 Direct was also removed as one of the recommended options.

Of the remaining two options, EOR and LOR, probabilities of success and development risk were overwhelming criteria. EOR had the lowest probability of safely landing on the moon and returning, nearly half that of the other three options (note that the two-launch versus single launch reliability was not considered in this paper). Although, EOR and LOR required the development of rendezvous and docking techniques and hardware; EOR had the additional requirements of propellant transfer, more use of cryogenic propulsion systems, and complicated launch operations due two launches in a short period of time.

This leaves LOR as the only solution that meets all of the constraints. Importantly, LOR enjoys the largest performance margin and has an independent lunar landing system optimized for its role, which reduces the mode's sensitivity to module growth. The one strong disadvantage that is pointed out by von Braun [3] is that the LOR requires a complicated maneuver of rendezvous and docking 240,000 miles from the Earth, where rescue is almost

Table 2 TOPSIS scores for 1962 modes

	1962 Modes	Apples to apples	Storable	LOX/LH2	LOX/CH4
LOR	0.799	0.810	0.860	0.656	0.804
C-5 DF	0.564	0.645	0.716	0.279	0.795
Nova DF	0.334	0.339	0.609	0.190	0.670
EOR	0.000	0.000	0.496	0.066	0.632

Table 3 FOM weights for LOR and C-5 DF

	Original weights	C-5 DF #1 weights
Production cost	4%	1%
Reliability	20%	31%
Ops cost	7%	7%
Development risk	20%	25%
Programmatic sensitivities	43%	34%
DDT&E	4%	2%

impossible. However, he stated that, "... this particular disadvantage is far outweighed by the advantages. . . ." [3].

B. Comparisons

In addition to the original four modes considered for Apollo, the detailed analysis was conducted for the "apples to apples" comparison and modes utilizing storable, LOX/LH2, and LOX/CH4 propellant combinations. The TOPSIS results for these three propellant types and the 1960s results versus the "apples to apples" comparisons are shown in Table 2. The most significant outcome of the analysis is that for each propellant combination considered the LOR mode was the best option. This states that it is the best architecture choice, and the selection of propellant types can be made independently in this study.

To see the impact of the weightings of the FOMs, the weightings were adjusted so that each of the other modes could become the best option. There were no weighting schemes possible to make the EOR or Nova DF modes the best. This is due to EOR representing the worst case for each of the FOMs and Nova DF being equal to or worse than C-5 DF in each FOM. The weightings required to make the C-5 DF the best option are shown in Table 3. The most significant changes are an increased emphasis on reliability and development risk with decreases in programmatic sensitivity weight and a slight decrease in production cost and DDT&E emphasis. These are simply a result of reducing LOR's advantages and boosting C-5 DF's advantages.

Figure 5 shows the plot of the TOPSIS rankings for each LOR propulsion technology option; it is a comparison between the three propellant alternatives for the LOR mode only. Storable propellant engines show much better DDT&E and development risk because they have been further developed and more widely used in the past. In the early 1960s, a LOX/CH4 engine had yet to be developed. Additionally, all three have the same operations cost because they all entail the same details after production of the elements through completion of the mission. The plot and scores show the LOR mode, with higher energy propellant types, would not have automatically generated a better system to land on the moon.

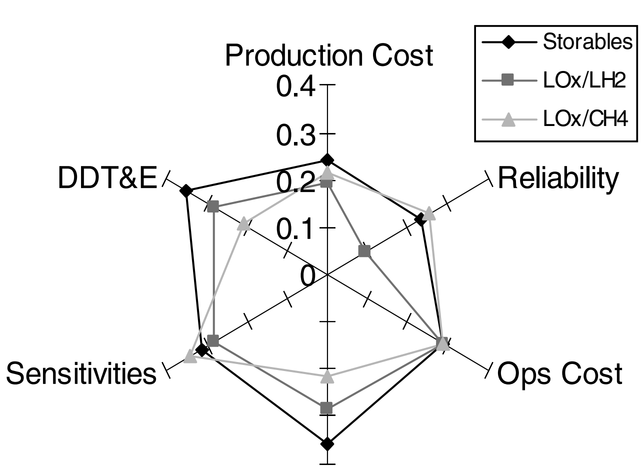

Fig. 5 TOPSIS rankings for LOR modes.

V. Modern Results

A. Mode Selection

To begin the present selection process, the original modes from 1962 were rerun through TOPSIS (Table 4) with the modern FOM weights assuming the same mission, payload, and technologies. The present weights, where reliability and costs are much more dominate, showed a significant effect on the final rankings giving the C-5 DF a clear advantage over the LOR and bringing the Nova DF much closer to the LOR because these architectures have less system elements that reduce total architecture reliability, production, and operations costs.

The results show the same order with the C-5 direct flight mode coming in first for all propellant systems. Second and third rank was a relative tie between the LOR and Nova direct flight modes with the Nova in second when using the storable and LOX/LH2 propellants and third in LOX/CH4 systems. These scores were too close to be able to make a clear distinction between the two. In a distant last was the EOR mode which ranked well below any other mode despite the propellant.

From this analysis, a C-5 DF architecture using storable propellants on the service and touchdown modules ranks the highest; however, TOPSIS is not a final selection tool and there are several high scores that rank closely. TOPSIS is designed to be a good first cut tool and here shows that EOR methods rank far below the others and can be eliminated from further consideration. With the similarities between the C-5 and Nova direct scenarios and the fact that the C-5 DF scored higher in all options considered, it can be argued that the Nova cases can be dropped as well. This should be done with caution and with the inclusion of experience or knowledge gained outside of TOPSIS. It should also be noted that the C-5 DF has little to no growth capability because it has smaller IMLEO delivery capability as compared with the LOR. Thus, an architecture mode should minimize the number of elements for reliability and costs, maximize the reliability for each element subsystem, and maximize the overall mass delivery capability with the smallest sensitivity to system mass growth.

B. Trends

Though TOPSIS does not give a final selection, several trends can still be seen. By looking at the C-5 DF modes shown in Fig. 6, it can be seen that the LOX/LH2 options are much more sensitive than the other options. This is due mainly to the hydrogen tanks which are very large as a result of the low density of liquid hydrogen; a slight increase in propellant mass results in a large increase in tank volume and subsequent structure. LOX/LH2 systems also suffer in reliability due to required cryogenic insulation hydrogen. These challenges also drive up the development and production costs as predicted by NAFCoM.

Table 4 TOPSIS scores with a modern mentality

	1962 Modes	Apples to apples	Storable	LOX/LH2	LOX/CH4
C-5 DF	0.886	0.891	0.905	0.702	0.839
LOR	0.736	0.734	0.776	0.476	0.766
Nova DF	0.679	0.699	0.790	0.621	0.754
EOR	0.000	0.000	0.373	0.155	0.351

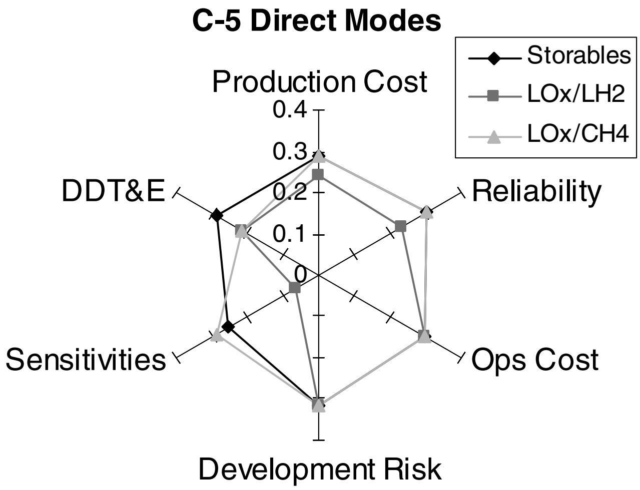

Fig. 6 Comparison of C-5 DF propellant systems with modern weighting scenario.

The storable and LOX/CH4 solutions are comparable in all FOMs except DDT&E cost and sensitivity. The higher performance of LOX/CH4 combined with its similar density to most storable propellants leads to a slight edge in sensitivities. NAFCoM predicts a lower DDT&E cost for the storable modes because of more experience in using storable propellants. The LOR modes give roughly half the IMLEO than the C-5 DF for each corresponding propellant option. On the other hand, the EOR modes have the highest IMLEO due to the tanker.

With these trends in mind, it is therefore recommended that further analysis should be performed on a direct lunar mission LOX/CH4 and/or storable fuels on all stages that are to be landed on the lunar surface. LOX/LH2 systems are recommended on all other stages, such as a TLIS and braking stage, for their increased performance.

Finally to make LOR the top ranked architecture for today's lunar missions, the total score for LOR was maximized by adjusting the FOM weights (see Table 5). In doing so, production cost, DDT&E, reliability, etc., have changed; however, these changes could have been the result of AHP if operated by "real" decision makers rather than the authors. Thus, sensitivity analyses should always be performed on the weights to determine architecture selections for further analysis.

VI. Summary

The 1962 Apollo architecture mode decision process was revisited with modern analysis and systems engineering tools to determine driving decision criteria and design decisions that may be used for NASA's current space exploration program. Results of the study concluded with the following:

1) The lunar orbit rendezvous mode ranked the best based on 1962 engineering, technology, and politics.

2) With greater emphasis on human safety and improvements in propulsion technology, a slight edge is given to the direct lunar mode over lunar orbit rendezvous. It appears that NOVA direct and earth orbit rendezvous (assuming a large launch vehicle must be developed) are not as competitive.

3) Reliability and development, operations, and production costs are major drivers in today's decision process because of more mature technologies and lower design uncertainties.

Table 5 Weighting scenarios to bring LOR to the top choice

	Modern weights	LOR #1 weights
Production cost	13%	1%
Reliability	33%	24%
Ops cost	33%	38%
Development risk	3%	5%
Programmatic sensitivities	5%	9%
DDT&E	13%	23%

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