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SURFACE EFFECT TAKEOFF AND LANDING SYSTEM (SETOLS)

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ARPA Program Report

SURFACE EFFECT TAKEOFF AND LANDING SYSTEM (SETOLS)

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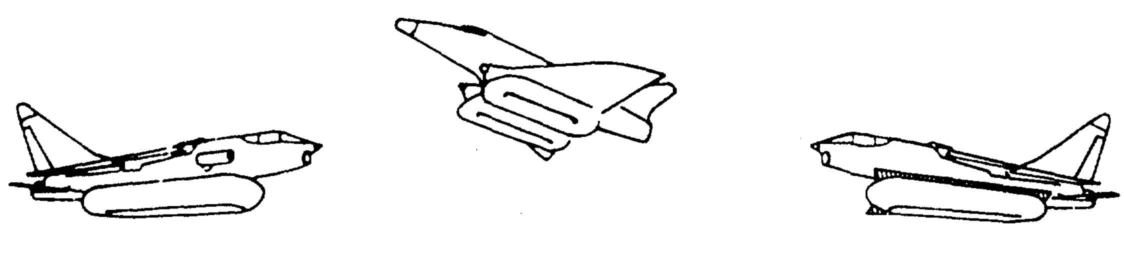

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An ARPA Program Report on its program to develop the surface effect takeoff and land system (SETOLS) for high performance naval carrier-based aircraft. The report discusses the program's background and technical need, the detailed plan to develop and demonstrate the technique, the program results, allocated resource levels, the contractor's performance and the program's impact.

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DEFENSE ADVANCED RESEARCH PROJECTS AGENCY PROGRAM REPORT

SURFACE EFFECT TAKEOFF AND LANDING SYSTEM (SETOLS)

SUMMARY

The British success with hovercraft stimulated in the United States and Canada studies of the further application of surface effect techniques to military problems. The surface effect ship (SES) and the advanced assault landing craft programs are two rather direct results. However, the application of these same techniques to aircraft, the subject of this Defense Advanced Research Projects Agency (ARPA) program report, was not obvious and had no similar precedent. ARPA, in an experimental and theoretical study from 1970 to 1973, assessed many of the technical problems related to applying surface effect techniques to the A-4 and F-8 carrier-based fighter aircraft. ARPA's involvement and program objectives resulted from a 1970 ARPA-IDA Workshop. At that time an existing joint Air Force/Canadian program to demonstrate the application of the surface effect landing system to the CC-115 Buffalo aircraft was reviewed, and an ARPA program to demonstrate the application to the higher density naval carrier aircraft was recommended.

The Naval Air Systems Command (NASC) acted as Contracting Office and the Naval Ship Research and Development Center (NSRDC) as Technical Director. Three industrial

contractors studied which of the two aircraft should be selected; two chose the F-8 and one the A-4. A committee evaluated the studies and concurred with the A-4 selection. Concurrently, studies of trunk materials, trunk flutter, arresting cable impact with trunk material, wind tunnel tests of the proposed configurations, and the dynamics of SETOLS landing were conducted. The program, which cost $995,000, was terminated when it became obvious that the Navy and Marine Corps were not then interested in having the program transferred.

BACKGROUND AND TECHNICAL NEED

1. Introduction

Near the end of the 1960's the amphibious hovercraft was viewed with considerable interest as a possible ship of the future because of low drag and resulting higher speeds. From this interest came the programs to apply the surface effect principle to other military problems, i.e. the advanced assault landing ship and the Arctic surface effect vehicle (SEV). During this time period 1968-69, the Bell Aerospace Company outfitted a small aircraft, the TOGW 2600-pound LA-4 amphibian, with the first SETOLS installation. The peripheral trunk configuration used was similar in design and operational characteristics to then-current SEV installations, including the cushion and trunk pressures (60 and 120 psf, respectively) and materials used. Retraction of the trunk was accomplished by utilizing elastic trunk material that hugged the fuselage surface when deflated. Ground and flight tests by Bell, later supported by the Air Force, demonstrated landing and takeoff operations from hard surfaced runways, turf, water, snow, and fine sand. The aircraft also demonstrated the ability to taxi over water, mud, low tree stumps, and empty and water-filled ditches. The flight tests indicated no significant changes in the aerodynamic stability and control characteristics of the LA-4 aircraft with trunk inflated or deflated. The effectiveness of inflatable pillow brake pads incorporated in the trunk was at least as good as a conventional wheel brake system. The cushion power was supplied by an auxiliary power unit in the aircraft driving a two-stage axial fan assembly. Subsequently, the Air Force, in a joint program with the Canadian Government, initiated a program to apply the Air Cushion Landing System (ACLS) to a low density aircraft. An ARPA-IDA Workshop in 1970 recommended that ARPA develop and demonstrate the feasibility of a surface effect takeoff and landing system (SETOLS) applied to a high density, high performance, tactical aircraft, including naval carrier takeoff and landing. NASC served as contracting agent and NSRDC served as technical agent for the ARPA SETOLS program. The program was initiated on 12 March 1971 when ARPA committed the first increment of funding in the amount of $495,000. The following paragraphs provide an assessment of the program, which was completed in December 1973. This paper and the attached list of references represent the documentation of the program.

2. Defense Problem Addressed

After the demonstration by Bell Aerospace Company of the amphibious capability of the ACLS on the LA-4 airplane, the U.S. Air Force formulated a joint program with the Canadian Government as equal partner to apply the technology to an intermediate density (41,000 pounds gross weight) CC-115 aircraft. Before selecting the CC-115 aircraft, the C-130 was considered. The much heavier "Hercules" C-130 (150,000 pounds) represented a considerable step from the LA-4 and was of no interest to the Canadians. Consequently the CC-115, Buffalo, judged to be rather a straightforward development with low to modest technical risk, was selected.

Application of SETOLS to Navy high performance, high density, tactical aircraft posed considerably different technical problems from those being addressed by the joint U.S. Air Force Canadian program: Could either existing or new-design aircraft be equipped with a SETOLS without adversely affecting either low or high speed performance?

Further, if the SETOLS replaces normal wheels, can this new type of aircraft be made compatible with catapult launch, carrier arresting system landing, and carrier flight deck handling without undue complexity? Finally, can the SETOLS trunk system have sufficient depth and area so that landing on moderately rough terrain is feasible? (Just the opposite characteristic of the design is required to minimize the effects on aerodynamic performance). The problem of operating a SETOLS-equipped aircraft on the surface of the open ocean was listed in the IDA-ARPA Summer Study but was ranked as a problem of low priority. This is because the requirement for size and type of skirt design for landing, takeoff, or flotation of the aircraft in the open ocean appeared unreconcilable with the size and aerodynamic consideration for a high performance combat aircraft. Also, the problems of jet engine ingestion of water and the general composite design of the aircraft implied by the open ocean requirement necessitated a complete new aircraft design. Accordingly, in this study the very limited water capability of the A-4 was outlined, and scale model landing dynamics tests were conducted.

The aircraft of primary interest in the SETOLS study are the tactical mission aircraft of the Air Force, the Marine Corps and the Navy, which have far different characteristics and requirements than the cargo planes. The Marine Corps and NAVAIR aircraft have the added unique and difficult problems of carrier landing and were, therefore, the aircraft selected for SETOLS program study.

The broad spectrum of military requirements involved in the application of SETOLS to high performance aircraft, together with the attendant technical risks made the program appropriate for ARPA sponsorship.

3. State-of-the-Art before ARPA Program

The LA-4 aircraft equipped with the ACLS, was flight tested from hard-surface runways, turf, water, snow, and fine sand. The aircraft also demonstrated the ability to taxi across mud, low tree stumps, and empty and water-filled ditches, and to take off from water. In November 1970, therefore, the Air Force began an effort to develop and install an ACLS on a low density CC-115 aircraft. In May 1971, the ACLS program became an International Cooperative Development Project between the Air Force and the Canadian Department of Industry, Trade and Commerce. The flight testing of the CC-115 aircraft that began in the spring of 1974 was expected to demonstrate the functional capabilities of the system, provide required design criteria, and establish guidelines in the areas of special maintenance, ground equipment, crew training, and logistical requirements. This program is estimated to cost approximately 14 million dollars.

We shall discuss in the next section the technical problems that will be investigated in the Air Force/Canadian program that are/were indicative of the state-of-the-art at the beginning of the ARPA program.

The Air Force/Canadian ACLS program is applying ACLSs to a cargo aircraft that has sufficient stability margins to accommodate the destabilizing ACLS cushion without requiring aerodynamic redesign. A second significant point about the selection of a cargo-type aircraft for SETOLS application is that it represents a simpler design task since it is built around a cargo volume and thus has a large fuselage section with sufficient area to conveniently locate a cushion system. Also, if local stiffening is added to the fuselage structure, trunk loads can easily be carried into the aircraft's other structure. Finally, the low sink rate requirements, together with the large cushion area available, enable the program to use conventional hovercraft skirt materials. This ACLS program, is, however, developing a variant of these materials that is stretchable when pressurized; accordingly, when not in use, the material collapses, holding itself close to the fuselage.

4. Technical Problems Investigated

The ARPA SETOLS program considered many problems that, for convenience in this report, are divided into three phases: (a) design of a SETOLS for a current, high performance, high density, carrier-based aircraft;

(b) performance analysis of a SETOLS-equipped aircraft; and (c) general assessment of the effect on aircraft utility and vulnerability, etc., due to SETOLS addition.

A. Design of a SETOLS for a High Density, High Performance Carrier Aircraft

(1) Is there a compromise possible between the aerodynamic stability problem with a large-area cushion using conventional fabric materials and a small-area cushion using higher strength materials? What are the properties of materials that could be developed for this application?

(2) Is the SETOLS-equipped aircraft compatible with the carrier catapult launch, arresting gear landing, flight deck, and general carrier landing of aircraft?

(3) Is the SETOLS-equipped aircraft capable of landing on an unprepared landing area? Is it amphibious?

(4) Can SETOLS be stowed so that when the aircraft is airborne its performance is not compromised?

(5) What are the detailed designs of the SETOLS trunk system, its attachment to the aircraft structure, and the air supply system and its detailed design characteristics?

B. Performance Analysis of a Carrier-based, High Density, High Performance Aircraft Equipped with SETOLS

(1) Are structural loads from high landing sink rates, i.e. 21 ft/sec, reduced with SETOLS?

(2) What terrain topography can a SETOLS-equipped aircraft land or take off from?

(3) Is flotation such that the aircraft can taxi, take off and land on soft surfaces, snow, ice, and water? What size and shape of obstacles can be negotiated as a function of speed?

(4) What are the dynamic problems of any of the components of cushion system during parking, taxiing, as a result of ground effects, and at flight speeds?

(5) Does SETOLS increase or decrease capability to land and take off in crosswinds?

(6) Are there techniques applicable to a SETOLS equipped aircraft which will provide both longitudinal forces used for braking and transverse forces used for aircraft handling?

C. Assessment of Effects on Utility and Vulnerability of Aircraft System Due to Addition of SETOLS

(1) Is the less positive steering of a SETOLS-equipped aircraft at intermediate and low speeds critical for carrier operation? For noncarrier operation?

(2) Does SETOLS addition to the aircraft decrease

its vulnerability?

(3) Does SETOLS addition reduce aircraft weight or must wheels be retained for ground handling and safety, thereby increasing weight?

5. Coordination with the Military Services

The Navy and Marine Corps, from the outset of the SETOLS program, have been fully aware of the objectives and status of the program. The initial proposal for the program was submitted by NASC, which was selected by ARPA to be the agent for the program. NSRDC conducted many of the program tasks for NASC. NASC, through NADC, awarded and monitored several contracts to private industry. The Marine Corps was kept abreast of program developments through a Marine Corps officer (NAVAIR Code AIR-03M), who participated in the 1970 ARPA-IDA Workshop and who thereafter became a member of the technical management team at NASC. Coordination with the Air Force, while informal, has been very extensive. The Air Force, as well as the Navy and Marine Corps, was heavily represented at an ARPA-sponsored review of the SETOLS program held in January 1972 (Ref. 1). A briefing on the Air Force ACLS Program was also presented to this review committee. Finally, many of the ARPA-sponsored efforts were reported at the Sixth Canadian Symposium on Air Cushion Technology, June 1972, (Refs. 2 and 3) and at the First American ACLS Conference in Miami, December 1972, and later published in the Proceedings

(Ref. 4). The Air Force, having their own program, has not contributed to the support of the SETOLS program; however, they have used the results of the SETOLS program, e.g. the technique to stop trunk flutter, as they found them appropriate. The Navy and the Marines, although interested, have not contributed financial support to the SETOLS program.

PROGRAM PLAN

1. Initial Plan

The initial program was divided into the following area phases:

A. The selection, by each of three aerospace contractors, of either the F-8 or A-4 aircraft for SETOLS application, preparation of a preliminary composite design of the aircraft with SETOLS, analysis of the systems performance, and development of a program plan for fabrication and test.

Concurrent with the preliminary design effort, a fourth contractor was selected to (a) explore alternate trunk cushion designs using surface effects phenomena, and (b) examine new materials for SETOLS application.

B. To accompany the composite design and performance analysis, a series of wind tunnel tests of the SETOLS aircraft was planned, progressing in detail and accuracy as the design progressed. Similarly, static and dynamic drop tests of the cushion system were also planned.

C. Upon completion of the above two phases, a request for proposal was to be issued for the detailed design and installation of SETOLS. The concept to be bid on would either be the best of the three or the best combination from the three.

D. Flight demonstration of the SETOLS equipped airplane.

2. Revised Program Plan

Midway in the above program the Navy (Ref. 5) recommended a revision to the ARPA SETOLS program. However, because the Ref. 5 plan did not reflect the recommendations of the ARPA review (Ref. 1) the program was directed to be consistent with Ref. 1. A formal revised program plan was never issued, but in summary the major elements of the plan are as follows.

A. Aircraft Cushion Dynamics -- Determination of aircraft/SETOLS dynamics during and after landing impact by quantifying the motions of three dynamically scaled 1/3-scale trunk models dropped from a moving carriage at the Landing Loads Facility at NASA Langley.

B. Arresting Cable Impact -- Determination of the behavior on impact of a trunk system with an arresting cable, considering material strength and model motions (to be conducted in conjunction with dynamic model tests).

C. Trunk Flutter -- Determination of the nature of trunk flutter when in proximity to the ground. The analytical approach will define the important structural and fluid parameters involved, and two-dimensional model trunk tests will support and verify the analytical results.

D. __Aerodynamic Characteristics__ -- Determination of the aerodynamic characteristics of the A-4 Boeing twin trunk combination in wind tunnel tests. The twin trunk configuration developed by Boeing for the A-4 aircraft was chosen because it promised advantages over a single trunk in terms of stability in ground effect (especially around the roll axis), ease of interfacing with the aircraft through hard points on the wings, and the inherent safety of retaining the test aircraft's normal landing gear.

E. __Over-Water Capability__ -- Determination of the drag and stability characteristics of a peripheral trunk system over deep water.

c. This revised phase of the program was funded for $[illegible]06,000, through December 1973. These funds were in addition to the $195,000 funding for the initial program.

__PROGRAM RESULTS__

The results to date of the initial and the subsequent revised program plans are as follows:

1. __Composite Design and Performance Analysis, SETOLS__

The Bell Aerospace Company, the San Diego Aircraft Engineering, Inc. (SANDAIRE), and the Boeing Company were contracted to confirm the feasibility of modifying either the T-28 or the A-4 aircraft to incorporate a SETOLS. Each company was asked to select one or the other aircraft and

D. Aerodynamic Characteristics -- Determination of the aerodynamic characteristics of the A-4 Boeing twin trunk combination in wind tunnel tests. The twin trunk configuration developed by Boeing for the A-4 aircraft was chosen because it promised advantages over a single trunk in terms of stability in ground effect (especially around the roll axis), ease of interfacing with the aircraft through hard points on the wings, and the inherent safety of retaining the test aircraft's normal landing gear.

E. Over-Water Capability -- Determination of the drag and stability characteristics of a perhipheral trunk system over deep water.

F. This revised phase of the program was funded for $500,000, through December 1973. These funds were in addition to the $495,000 funding for the initial program.

PROGRAM RESULTS

The results to data of the initial and the subsequent revised program plans are as follows:

1. Composite Design and Performance Analysis, SETOLS

The Bell Aerospace Company, the San Diego Aircraft Engineering, Inc. (SANDAIRE), and the Boeing Company were contracted to confirm the feasibility of modifying either the T-8 or the A-4 aircraft to incorporate a SETOLS. Each company was asked to select one or the other aircraft and then complete a preliminary design of the required modification and analyze the resultant performance. These two aircraft were selected since they represented aircraft that were currently operational and available for use as an experimental platform. The choice as to whether to keep the landing gear or not was left to the individual study. A summary of the results of each follows.

A. The Boeing Company selected the McDonnell Douglas A-4 aircraft to outfit with the SETOLS, on the basis that the engine inlets are located above the wings, thereby minimizing engine ingestion of water spray and debris. In addition, the existing landing gear attachment is convenient to attach SETOLS support pods of sufficient size to house deflated skirts, solving possible bag flutter and unwanted parasitic drag problems. The resultant configuration resulted in two trunks, one under each wing, in contrast to the Buffalo single trunk. In preparation for landing, the pods would open, and the air-inflated SETOLS trunk would protrude. This design retained the normal landing gear and was so designed that capability of wheels-down landings was preserved, solving safety and ground-handling problems but adding to the weight of the aircraft. The two separated pods leave clear access to the underbody of the aircraft for attachment of weapon stores, catapult attachment, and normal arresting hook; in addition, the wide footprint of the two trunks provides considerable lateral ground stability not available in a single trunk. Slight changes were required to the horizontal tail to compensate for reduced low-speed-aerodynamic directional stability caused by the added pods. Performance aspects are discussed later in this report. The Boeing study is documented in Ref. 6.

B. The Bell Aerospace Company selected the F-8 aircraft to equip with SETOLS. This aircraft, having greater thrust-over-drag margin and greater volume available for equipment, suggested a cushion design and material requirement very similar to that of the CC-115 SETOLS system, i.e. lower cushion pressure, and operation at lower angles of attack at takeoff. It did not, therefore, require a dynamic nose pop-up mechanism to provide the required angle-of-attack for takeoff. The Bell SETOLS design removed the landing gear and placed a contiguous trunk below the fuselage. The cushion system extended aft, terminating just forward of the carrier arresting cable hook. The trunk materials recommended were stretch-type materials that would retract against the fuselage when not pressurized. A separate air supply system was added. The catapult attach was extended slightly and located forward in the cushion cavity. During catapult a portion of the trunk was deflated to permit attachment to the catapult. A larger vertical stabilizer was required to compensate for decreased low speed directional stability. Because the design had no wheels, flight deck handling was done either by taxiing or the use of tractors, keeping the cushion inflated, or, by use of a parking bladder, the aircraft would be parked on a wheeled dolly if it were desirable to move the aircraft without operating the jet engine and cushion auxiliary power unit. Its performance is discussed later in this report. The Bell study is documented in Ref. 7.

C. <u>The San Diego Aircraft Engineering, Inc. (SANDAIRE)</u> selected the F-8 for SETOLS because of (a) the aircraft's low ground clearance, (b) low angle of attack because of its variable incidence wing, (c) no center-line body stores, and (d) the high wing that has minimum effect on general stores and on the SETOLS when deployed. The SANDAIRE design incorporated ground handling gear and brakes as necessary for safe, efficient handling of the aircraft on a carrier. The handling wheels were of conventional design; however, they were smaller and lighter in weight than those of the F-8 since they were designed only for taxi and takeoff. The question as to whether the aircraft can be safely catapulted with SETOLS was not resolved in this limited study.

This SETOLS design houses in the center fuselage a racetrack-shaped contiguous trunk cushion. After takeoff the cushion is tracted into the fuselage and doors close over the deflated cushion material to protect it from the windstream. The gross weight of this SETOLS F-8 aircraft is slightly less than standard the F-8H. The stability of the aircraft was found to be affected by the SETOLS addition; however, the extent of aerodynamics platform revisions required to compensate was not determined. The SANDAIRE study is documented in Ref. 8.

b. Other Studies. In addition to the three specific aircraft designs for applying SETOLS, an analytic study of skirt systems and materials for SETOLS application was performed by the Goodyear Tire and Rubber Company. NSRDC either conducted, or were technical monitors for, a series of theoretical and experimental studies. The Goodyear is summarized as follows, the NSRDC work in the next section.

- The Goodyear Tire and Rubber Company evaluated promising air-cushion concepts, established power, inflation pressures, and carrier impact load requirements, evaluated catapult feasibility and evaluated and reviewed material requirements and folding characteristics.

Goodyear, in its report (Ref. 9), concluded that:

(1) Flexible-skirt air cusions are feasible for carrier-based aircraft.

(2) Peripheral jet designs are preferred, whether single lobe or multilobe, providing sufficient lubricating air with nominal to low power requirements.

(3) Designs are relatively simple and can use conventional materials and fabrication techniques. The systems can be retracted and enclosed in a compartment. Conventional, non-stretch materials are more efficient and are preferred over the pliable materials.

In summary, the four studies did not agree on all points. Some of the areas of disagreement were pertinent to SETOLS while others were not. However, the following technical issues are evident.

- New high pressure trunk materials, whether of the conventional type or stretchable, were not considered.
- The Boeing study briefly considered landing and takeoff on water. It concluded that for take off even on a smooth sea, thrust for the A-4 was marginal to accelerate the aircraft thru hump speed. Accordingly, they concluded that, for the aircraft considered, takeoff and landing on protected water was the only practical possibility and that the

aircraft would have to exceed hump speed, i.e., 8 knots before reaching the water.

- The handling of a SETOLS-equipped aircraft on a carrier remains a problem.

2. The Naval Ship Research and Development Center

NSRDC served as the technical steward of the SETOLS program. Their interim and final reports are Refs. 10 and 11, respectively. The following summary, drawn from Refs. 10 and 12, is consistent with but briefer in detail than Ref. 11.

A. Wind Tunnel Tests

One-tenth scale models of each of the contractor's proposals, with their versions of SETOLS installed on the F-8 or A-4 aircraft, were tested initially at NSRDC to obtain the effect of SETOLS on the aircraft's static longitudinal and lateral aerodynamic stability and control characteristics. The deployed trunks were not supplied with airflow, nor were ground effects simulated. The results of these preliminary tests are documented in Refs. 13 and 14 and were used by the contractors to update their proposals.

Upon selection of the A-4 Boeing SETOLS configuration as the suggested ARPA demonstration configuration, another more meaningful test was made with simulated trunk airflow both in and out of ground effect conditions. This was a 22 percent scale model test conducted at the LTV Aerospace Corporation low speed wind tunnel. Briefly the results of this test can be summarized as follows.

(1) No abrupt changes are introduced into lift and pitching moment characteristics of the A-4 with the SETOLS configuration, and the data are quite linear to an angle-of-attack of 18 degrees, which should be sufficient for most landings or takeoffs.

(2) While there is a slight loss in control surface effectiveness, both stabilizer and flaps are effective over the range of angles-of-attack for takeoff and landing, with sufficient stabilizer control for trimming the aircraft.

(3) The SETOLS-equipped A-4 aircraft shows a reduction in the total in-ground-effect drag with cushion air flow compared to the conventional A-4 aircraft.

(4) The lateral stability was improved for the in-ground-effect condition; however, a loss occurs for the out-of-ground effect condition (landing approach). The addition of vertical stabilizers on the horizontal tail will recover much of this loss.

(5) There was a loss in directional or weathercock stability; however, addition of the auxiliary vertical

stabilizers resulted in a configuration with more directionally stability than the conventional A-4 aircraft.

It should be noted that these results are based on the reference center-of-gravity (cg) for the stability and control data fixed at the A-4 wing quarter mean-aerodynamic-chord point. Additional testing would be required to define aerodynamic performance should the cg history for the A-4 with SETOLS over its mission profile be significantly different than for the unmodified A-4. The full results of these tests are given in Refs. 15 and 16.

B. Testing of SETOLS Aircraft Landing Dynamics

The analysis of the energy absorption capability of the air cushion attached to a high density airplane had had little or no verification. Consequently, scale models of the various trunk configurations on the F-8 and A-4 aircraft were tested with static drop tests. Also, one of the Goodyear designs was tested on the F-8 model. All cushion designs decelerated the vertical velocity of the models with ample margin, so small-area, moderate pressure cushion systems are considered feasible in this respect.

In addition to the static tests, the Boeing design is planned to be dynamically scaled and towed, to be released at landing speed and normal sink rates. Aircraft surface damping due to wings and tails will not be represented in these tests. These tests are to be conducted at the Landing Loads Facility, NASA, Langley, at their convenience--currently scheduled in late CY 1974. Although these tests and simulator tests conducted in support of the Air Force program are, in effect, two dimensional, they will indicate whether or not there are dynamic problems, which will most surely be aggravated when a third degree of freedom is added and with a carrier landing.

C. Impact on Cushion and Arresting Cable

The Landing Loads Facility, NASA, Langley, also tested the effect of the impact of arresting cables on cushions, using simulated carrier landings. The Bell F-8 trunk model showed no adverse dynamic behavior after impacting the cable arresting system. No damage was evident to the trunk material after repeated impacts, the trunks being stiff enough that the fabric does not wrap itself around and capture cables; this was a predicted problem of some concern.

D. Trunk Flutter

Flutter exists in the trunk material when the trunk is close to the ground surface. This was observed in all the dynamic tests. Two-dimensional flutter characteristics as functions of trunk and cushion pressure, air flow, peripheral jet air velocity, and ground clearance were measured for correlation with an analytic model (see Ref. 17). The analytic model has been developed by NSRDC, but has not yet been published. A series of fixes were evaluated experimentally that damped the flutter sufficiently for the dynamic tests, and many of these techniques are being applied in the Air Force program. Until full-scale dynamic landing and takeoff tests are conducted, it is difficult to tell whether flutter is a severe problem or merely a transient phenomenon that is passed through so rapidly that it can be ignored except in static tests. This is an area demanding further effort, which it will most probably receive under the Air Force program.

E. Scale Model Tests of SETOLS on Water

In order to investigate the operation of SETOLS over water, powered scale model tests of peripheral inelastic trunks with a range of length-to-beam ratios (2:1, 4:1 and 6:1) were conducted in the low speed tank facility of the Lockheed Ocean Laboratories, San Diego, California. Tests were completed in August 1973, and data show that pitch stability is very sensitive to length-to-beam ratios, the 2:1 being unstable for all test conditions. This is an area that requires considerable additional work and most probably will not be encompassed in the joint

Air Force/Canadian program. This work is documented in Ref. 18.

3. Follow-on Plans

Neither the Navy nor the Marine Corps, in assessing the transfer and possible use of the SETOLS technique, could correlate a mission with high enough priority, with the proposed demonstration on the A-4 and accordingly could not justify transfer. It was at this point that ARPA decided to terminate the program.

RESOURCE LEVELS

The SETOLS program was initiated in FY 1971 with the commitment of $495,000 under ARPA Order No. 1755, to NASC. The program was continued in FY 1972, with the same agent, with the commitment of $500,000 under ARPA Order No. 2121. The funding distribution by task and organization is shown in Table 1, which reflects the fiscal year in which funds were obligated.

TABLE 1

TABLE OF PROGRAM FUNDING (THOUSANDS OF DOLLARS)

Task/Organization	FY 71	FY 72	Total
Feasibility Studies:			360
NSRDC	*		
Bell	*		
Boeing	*		
Sandaire	*		
Goodyear	*		
NADC	*		
NASC	*		

*Indicates year in which performer's activity was funded.

Table I (contd.)

Task Organization	FY 71	FY 72	Total
Aircraft Trunk Dynamics:			251
NSRDC	*	*	
Bell	*	*	
Goodyear	*		
Boeing		*	
Arresting Cable Impact:			20
NSRDC		*	
Trunk Aerodynamics:			126
NSRDC		*	
LTV		*	
Trunk Flutter:			42
NSRDC		*	
SW Research		*	
Water Characteristics:			196
NSRDC		*	
Lockheed		*	
Centro Corp.		*	
NADC		*	
TOTAL	495	500	995

CONTRACTOR PERFORMANCE

Discussion of the results of the studies of performance of the SETOLS-equipped aircraft is best accomplished against a background of the technical issues. The ARPA program addressed the following points.

1. The Composite Design of a SETOLS-equipped Carrier-based Aircraft

The composite design studies did not stress the development of, or show what was possible in advanced state-of-the-art, small, high-strength cushions, and as a result, all designs showed that current conventional cushions could be adapted to the carrier aircraft. Implicit with the use of conventional cushions, there are compromises in the low speed aerodynamic and overall performance of the aircraft. The redesign of the aircraft to minimize the effects is, of course, a substantial task and, accordingly, was only addressed fleetingly with the Boeing design.

The aircraft with state-of-the-art large cushions can be designed to be compatible with carrier catapults and arrested landings; however, handling the SETOLS aircraft on a carrier flight deck remains a potential problem. The ARPA study concentrated perhaps too much on the carrier problem and neglected the more significant and challenging problem, i. e. can the SETOLS aircraft land on an unprepared runway. The requirements for obstacle clearance, trunk depth, and flexibility for a landing or takeoff from a rough, unprepared runway lead to a large trunk design, antithetical to the requirement to keep cushion area and extension from the aircraft as small as possible to minimize the aerodynamic destabilizing effect.

Also necessary is a definition of an unprepared runway. Here the allowable size and spacing of undulations as a function of cushion size were not defined, although these are important as they approach the dimensions of the SETOLS cushion height and length, and, consequently, must be quantified for each specific aircraft and cushion design. Obviously the cushion can be designed to operate over a considerable range of obstacle topologies at the expense of power, cushion depth and size, and effect on aircraft stability and control. Finally, the porosity of the surface is important and must be considered.

2. The Amphibious Capabilities of a SETOLS-equipped Carrier Aircraft

The ARPA SETOLS study indirectly illuminated the question of whether a high performance aircraft equipped with SETOLS can operate from the surface of the open ocean. The answer appears to be that, if SETOLS is added to an existing high performance aircraft, the addition adversely affects stability and control of the aircraft unless the volume of the trunk system and its projection from the aircraft is minimal. The requirements for operating on the open ocean, i.e. flotation, takeoff, and landing, argue for exactly the opposite, that is, a deep, large trunk system that allows operation in high sea states and protect engines against water ingestion, which is the current nemesis of jet engines working close to the water surface. Nothing in the studies is optimistic about the potential ability of current types of carrier-based, high performance aircraft equipped with SETOLS to operate, takeoff, or land in the open ocean.

Finally there is the question: Can the SETOLS be stowed so that when the aircraft is airborne, its performance is not compromised? The SETOLS can be built with (a) conventional, rigid materials that can be folded into a closed compartment during flight, or (b) with elastic materials that can be used to withdraw the material into the same compartment. The current Air Force program will evaluate the effectiveness of elastic materials being drawn against the craft superstructure yet exposed to the air stream. At high speeds, this is not judged practical.

3. Analysis of the Performance of SETOLS-equipped Carrier Aircraft

The SETOLS design studies concluded that it appears feasible to catapult the aircraft with SETOLS active; however, there are differing points of view as to whether it is practicable. This is an area where further study and a test would be helpful.

Arrested landings are entirely feasible, and SETOLS offers eventually a more benign environment for pilot and aircraft during deceleration than does a conventional landing gear. Interaction of the cushion and the arresting cable does not appear to be a problem. The impact attenuation, using SETOLS with current large-area deep cushions, appears feasible and practicable; however, the detailed design of the method of energy dissipation, whether in the air supply and/or vents on the trunks, requires further study. Addition of SETOLS to an A-4 aircraft reduces the positive braking of the aircraft on landing and increases the run-out upon landing on a conventional hard-surfaced concrete runway from 2750 to 3250 feet. This is a subject that demands additional study; and most surely it will be considered in the Air Force program.

The ARPA and Air Force test program progressed far enough to identify that there are three-dimensional damping problems associated with landing with a SETOLS-equipped aircraft on a hard surface. Also a transient trunk flutter problem was found, though it may not be a problem in the changing dynamic situation of landing or take off or over soft surfaces. The Air Force program will of necessity resolve both of these problems. A third dynamic problem is that associated with operation over water.

Finally, there is considerable increase in aircraft crosswind landing and takeoff ability; however, ARPA studies did not quantify the increase.

4. Assessment of Effects on Utility and Vulnerability of an Aircraft due to Addition of SETOLS

In general, the addition of SETOLS brings mixed blessings. The SETOLS-equipped aircraft is not as sensitive to the roughness or hardness of the runway as is the wheeled aircraft; yet it must pay for this by an increase in aircraft total drag when SETOLS configuration and auxiliary air supply system are included. The performance of the aircraft accordingly suffers slower speed, requiring longer runways to become airborne or to stop. The impact on aircraft performance due to the addition of SETOLS is dependent upon whether the aircraft is designed with SETOLS from the beginning or whether SETOLS is added as an after thought. Ground handling, particularly on a carrier, requires wheels, which probably have to be comparable to today's wheels so that emergency landings are possible. So there probably is a weight penalty; however, the redundancy of landing capability is desirable.

SETOLS provides the ability to traverse small obstacles and steps; however, this ability must be qualified as to the number, spacing, and location of such obstacles in relation to the dynamics of either landing or takeoff.

SETOLS may afford the capability to operate from a battle damaged but not cratered runway, but so may an aircraft with conventional landing gear. However, a SETOLS aircraft has a considerable advantage in that it can land in areas adjacent to a hard-surface runway or run off the end of a runway with some impunity, which is difficult with high density aircraft with conventional gear.

The addition of SETOLS, together with wheels, should decrease aircraft losses since the two systems available for landing would increase aircraft reliability and life expectancy. A further point is that the air cushion is provided with holes for releasing air, so, additional holes or rips will not critically degrade performance too rapidly.

At this time it appears that the addition of SETOLS to existing craft will increase the aircraft weight, whether or not the wheels are retained for safety and handling; therefore, performance will suffer. However, for new designs, there is a potential for reducing aircraft weight.

Finally, the lack of positive steering of a SETOLS-equipped aircraft at intermediate and low speeds on a wind-swept rolling carrier deck is considered a critical problem and may dictate the retention of some forms of wheels or alternates such as tractor lift/tow/skid system.

PROGRAM IMPACT

1. Actual Impact on Other Programs

The Air Force/Canadian ACLS program has used a solution developed by Bell and NSRDC in the early stages of the ARPA SETOLS program to alleviate trunk flutter problems experienced in model tests. This solution includes installing a strake to provide flow separation and adding concentrated masses at appropriate locations on the trunk. The detailed measurements by Southwest Research Institute (Ref. 17), and their recommendations, will allow design of a cushion system where flutter is either eliminated or minimized. Another program that has used data generated in the SETOLS program is the Air Force program to apply SETOLS to a Jindivik RPV. Two innovative features that emerged from the initial SETOLS feasibility studies are the concept of the inelastic trunk and the use of a fan employing a tip turbine driven by propulsion-engine bleed air to supply ACLS air; both of these have been used in this program. The Jindivik program began with feasibility studies in FY 1972 and is scheduled to end with flight tests in FY 1975.

2. Potential Impact on Other Programs

Program results may be useful in developing new concepts of operation (i.e. from unprepared runways, etc.), the definition of new missions (not requiring prepared landing fields), and the further comparison of the SETOLS concept with more conventional systems. As the Air Force and the Canadians look past the medium density CC-115 aircraft to higher density and higher performance aircraft, the ARPA efforts on composite design, materials, and the dynamics effort completed by ARPA will be directly applicable.

3. Impact on the State-of-the-Art

Specific advancements in the state-of-the-art that did occur included:

- Design techniques and material fabrication procedures developed through preliminary design for a retractable air-cushion landing gear system;
- The dynamics of a SETOLS-equipped aircraft during high speed, high-sink-rate landing operations characteristic of naval aircraft determined and demonstrated experimentally in dynamically scaled tests;
- Flight-rated, auxiliary power systems to supply cushion air flow defined;
- Parameters of trunk flutter determined

experimentally and trunk flutter minimized;

- Operation of high performance, high density aircraft on soft unprepared runway over an obstacle of moderate size;

- The ability of a SETOLS cushion to withstand repeated impacts with carrier arresting gear demonstrated in dynamically scaled tests;

- The ARPA program, taking essentially the same cushion pressures used in the Air Force and Canadian CC-115 cushion system and with conventional materials, showed they could be applied to much higher-density and higher-performance aircraft.

4. Program Transfer

Other than the interchange of SETOLS program technology already mentioned, there are no present Navy mission requirements for the results of the program. On the other hand, should a future requirement for SETOLS effort materialize, much of the SETOLS program output can be directly carried out into the next design phase.

5. Future Research

The Air Force and Canadians will continue the development of materials, auxiliary systems, and analysis of the dynamics of air-cushion landing systems as part of their CC-115 program. The following are areas recommended for future development in the event a future ACLS program is initiated:

A. How to minimize the ingestion of water and debris during takeoff and landing.

B. How to design a jet engine to withstand ingesting water and debris.

C. How to augment directional stability and control during low speed operation of SETOLS aircraft.

D. How to improve SETOLS aircraft handling on the ground, flight deck and hangar deck.

E. How to optimize energy dissipation during landing--the-trade-off between fan characteristics and trunk pressure relief valves.

F. How to increase braking of SETOLS aircraft.

G. Establish effects of dynamics of vehicle motion on flutter dynamics and threshold.

H. Establish the effects of surface roughness of both the ground and cushion trunk design on flutter.

I. Test three-dimensional models of trunks and correlate with theory.

J. Determine the limits of strength characteristics of cushion systems, consistent with delamination and flexibility requirements if higher strength fibers or metals are used.

6. Current Organizational Contacts and Identification

Following is a brief list of organizations and specific individuals' names where inquiries for information or assistance regarding SETOLS or ACLS can be addressed.

A. Defense Advanced Research Projects Agency (ARPA): Mr. A. J. Tachmindji, Deputy Director or Dr. F. W. Niedenfuhr

B. Naval Ship Research and Development Center (NSRDC Code 161): Mr. Elmer Burgan

C. Naval Air Systems Command (NAVAIR 03P31): Mr. John C. Vaughan

D. U. S. Air Force Flight Dynamics Laboratory, W-PAFB: Dr. K. Digges or Mr. William Lamar

E. The Boeing Company, Seattle: Mr. Lloyd Gardner

F. The Bell Aerospace Company, Buffalo: Mr. Colin Faulkner

G. Goodyear Tire and Rubber Company, Aviation Division: Mr. L. Peelman or Mr. F. M. Milhoan

H. San Diego Aircraft Engineering, Inc.: Mr. George Lutz

I. Southwest Research Institute, San Antonio: Mr. R. L. Bass or Mr. J. E. Johnson

J. Lockheed Missiles and Space Company, Ocean Laboratory, San Diego: Mr. R. G. Wright

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