EVALUATING THE C-17 SEMI-PREPARED RUNWAY CAPABILITY – AN OFF-ROAD MAP

GRADUATE RESEARCH PROJECT

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Abstract

The Army and Air Force jointly satisfy the Defense Planning Guidance requirement for forcible entry into non-permissive environments through Strategic Brigade Airdrop (SBA). The C-17 is the aircraft of choice for the SBA due to its outsized cargo carrying capacity, unlimited range due to air refueling and short landing capability. When performed solely by the C-17, the SBA consists of 53 airdrop (Alpha Echelon) and 48 airland (Bravo Echelon) sorties to deliver the XVIII Airborne Division's Ready Brigade-Medium

This paper focuses on the challenges of delivering the Bravo Echelon to a single semi-prepared runway (SPR) within the 20-hour window, a capability the C-17 has yet to demonstrate. The yet-to-be-resolved issues include the ability of SPRs to support the weight of the C-17, the inaccuracy of takeoff and landing data, and the inability to predict the ability of targeted SPRs to support intended operations. While these issues have not yet proven insurmountable, they do provide formidable challenges which will require a concerted effort by all agencies involved in order to make the Strategic Brigade Airdrop Mission a credible deterrent and one which military commanders will be willing to employ. This paper highlights the issues and provides a roadmap for transformingconcept to reality.

I. Introduction

"A semi-prepared runway (SPR) is an unpaved runway based on compacted native soils/aggregates designed to support the intended mission."

--- AMC Briefing 21 Dec 00

Background

A semi-prepared runway is an unpaved landing surface which has been cleared of debris and obstructions. Since the beginning of mechanized flight, aviators have been landing on semi-prepared runways. Large concrete runways were not necessary since the relatively simple technology of early airplanes limited the potential for damage from landing on semi-prepared runways. Throughout the history of US military aviation, from WWI to Afghanistan, semi-prepared runways have been used extensively for military operations of all types. But, in spite of all of the historical experience, operating on semi-prepared runways is becoming more of a challenge with the growth in the technological complexity and size of modern aircraft. This is especially true in the case of the Air Force's newest airlifter, the C-17 Globemaster III. Although the C-17's semi-prepared runway capability has been evaluated and validated, the ability of the C-17 to support the entire range of missions has not been fully addressed. This paper will examine the current capability of C-17 semi-prepared runway operations and highlight the shortcomings as well as possible impacts on current and future missions. In order to more fully understand the value of this capability, it is necessary to understand the past utility associated with landing on semi-prepared airfields.

The World Wars

From WWI through World War II, the ability to land on semi-prepared runway was commonplace. Since World War II, the frequency has diminished, but the capability has nevertheless been very important.

Korea

During the Korean Conflict the challenges associated with operating from semi-prepared runways began to mount. James A. Huston, author of *Guns and Butter, Powder and Rice,* a book describing the logistical challenges of the Korean Conflict identifies the difficulties associated with landing larger aircraft on semi-prepared airfields He writes:

> Only Kimpo had a paved runway. During periods when the areas were in the hands of Communist forces, allied forces bombed the airfield to such an extent that they could not be used until after extensive repairs. Then the heavy traffic of cargo planes made continuous maintenance necessary in order to use the runway at all. (Huston, 1989)

Vietnam

During the Vietnam Conflict, jet-engined fighters and bombers required long runways and concrete ramps, but tactical airlifters such as the C-123 Caribou and the C-130 Hercules routinely landed on various types of semi-prepared runways. The aerial re-supply during the siege at Khe Sanh is one of the more well-known examples of tactical airlift aircraft flying re-supply missions to semi-prepared runways. During this siege, the C-123 and the relatively new C-130 flew re-supply missions to Khe Sanh, a remote US Marine outpost with a semi-improved runway overlaid with pierced steel planking, providing the outpost with much-needed ammunition and other supplies. According to the official history of tactical airlift during the Vietnam War:

> Airlift made possible the allied victory of Khe Sanh in 1968. For eleven weeks early in the year, the defenders of this post were exclusively re-supplied by air and withstood the attacks of four North Vietnamese regiments. The campaign bore comparison with the classic combat airlifts of Stalingrad, Burma, and Dien Bien Phu. (Bowers, 1983: 295)

Operations DESERT SHIELD/DESERT STORM

During Desert Shield/Desert Storm, C-130s were heavily used in delivering intra-theater cargo and was critical during the "Hail Mary Pass" when the XVII Corps drove north to the Euphrates River and then east to encircle the Iraqi Republican Guard. To facilitate the "Hail Mary Pass", C-130s transported 9000 tons of equipment and 14,000 personnel to the town of Rafha in the vicinity of the Trans-Arabian oil pipeline. Some missions used sections of narrow highway, some used semi-prepared runways (Gulf War Air Power Survey, 1993:158).

Operation ALLIED FORCE

Although modern aircraft are much more complex and susceptible to damage from landing on semi-prepared runways, the military utility associated with landing on dirt remains a valuable commodity . Operation ALLIED FORCE, the combined air offensive waged to expel the Serbian army from Albania and halt the ethnically motivated aggression against the Kosovar Albanians provides an example where landing on dirt could have been used to enhance operations. During Operation ALLIED FORCE, the only aerial port of debarkation (APOD) being used by the coalition forces in Kosovo was Rinas Airfield near Tirana. Rinas Airfield became bogged down due to the amount of airlift required to support the simultaneous military and humanitarian airlifts and heavy rains which rendered portions of the airfield unusable. During advanced planning for the airlift of Task Force Hawk, the Director of Mobility Forces (DIRMOBFOR) for

Operation ALLIED FORCE, (then) Colonel Rod Bishop explored the possibility of opening an additional APOD at Kukes, an airfield with a semi-prepared runway 50 miles north of Tirana (Bishop, 2002). Following an initial site survey at Kukes, it was determined that the semi-prepared runway could only support 6 to 8 C-17s landings before the airfield would have to be closed for repairs. This limitation coupled with other developments in the military campaign negated the requirement for an additional APOD and Tirana remained the sole APOD for the theater. Had the need remained for an additional APOD, Kukes could have relieved congestion at Tirana and may have potentially shortened the conflict by expediting the employment of military options.

Operation ENDURING FREEDOM

During Operation ENDURING FREEDOM, the war against terrorism, the C-17 has proven invaluable since it was the only aircraft in the Air Force inventory capable of flying the outsized equipment over the required distances and landing on semi-prepared runways. The C-17 delivered two Marine Expeditionary Units (64 sorties, 970 short tons, 481 passengers) to Rhino LZ, a 6000 foot long unstabilized semi-prepared runway 80 miles southwest of Kandahar. Although the MEU deployment to Rhino LZ was successful, it was not without it limitations since the runway required extensive repair every day following the eight sorties flown during the previous night's operations. The following sections of this paper contain lessons learned from Rhino LZ operations.

Wake Up Call

The determination that Kukes Airfield could only have handled a minimal amount of C-17 traffic should have served as a wake-up call to many in the mobility community.

While other developments in the air war precluded the need for Kukes Airfield during Operations ALLIED FORCE, the limitation identified by the site survey team could have been a show-stopper had Kukes, in fact, been needed for achievement of the military objectives. This wake-up call should have alerted interested parties that the C-17 semi-prepared runway capability may not be as robust as was previously believed. Operations at Rhino LZ, although very successful, shed more light on limitations of the C-17's semi-prepared runway capabilities.

This is not to say that the C-17 is not semi-prepared runway capable, but it is to say that this capability is not as routine as many interested parties would think. Landing a 447,000 lb C-17 on semi-prepared runways and more importantly stopping it in 3000 feet presents challenges never before encountered when landing smaller, lighter, aircraft such as the C-123 or C-130 on semi-prepared airfields. The challenges increase significantly when a scenario calls for frequent C-17 landings on the same semi-prepared runway without allowance for runway maintenance. The true status of the C-17's ability to routinely land on semi-prepared runways should be of great interest to the U.S. Army community since the Army stands to lose the most if the C-17 semi-prepared runway capability is not as robust as believed. This ability to land on a semi-prepared runway coupled with the other tactical qualities of the C-17 prompted the Army to stand solidly behind the C-17 purchase when many lobbied in favor of other options. This support was primarily due to the belief that the C-17 could and would routinely land on semi-prepared runways in support of army objectives. Another major reason for support of the C-17 over other options was the stated ability of the C-17 to support both the Alpha and Bravo echelons of the Strategic Brigade Airdrop mission.

Strategic Brigade Airdrop

While there are numerous scenarios where that Army would need the Air Force to land on a semi-prepared runway, the most demanding scenario is the Strategic Brigade Airdrop, or SBA, mission. The SBA mission offers a theater commander the ability to forcibly enter a threat area anywhere on the globe and conduct military operations following the securing of an objective through aerial assault. The Defense Planning Guidance (DPG) (Rumsfeld, 1996) directs the services to jointly provide the Strategic Airdrop Mission capability in support of national political and military objectives. The DPG requires the US military to maintain the capability to execute the SBA within some prescribed distance within 48 hours of notification.

The SBA concept has been utililized on a smaller scale during contingencies such as Operation URGENT FURY in Grenada, JUST CAUSE in Panama, and UPHOLD DEMOCRACY in Haiti. Although these operations included troops insertions by airdrop, these contingencies cannot be considered true SBA missions since they did not cover strategic distances and US troops were already present on the ground. However, these examples demonstrate the effects of an airborne insertion, especially in the case of Operation UPHOLD DEMOCRACY when the de facto Haitian leadership capitulated when they learned that U.S. cargo planes loaded with elite US Army Rangers were enroute.

Statement of the Problem

The C-17 cannot currently deliver the SBA Bravo Echelon to an unstabilized semi-prepared runway. The current preparation time required to strengthen the weight bearing capacity unstabilized runway to the level which can support the number of sorties required for the Bravo Echelon insertion is at least 45 days. This shortfall limits the options available to commanders in the same way these limitations could have limited Colonel Bishop's options in Kosovo had the requirement for an additional APOD persisted. In addition, these limitations could force a commander to forfeit the key elements of forcible entry -- speed and surprise -- and select a hardened airfield for the SBA insertion. Because hardened runways are normally found in populated areas, selecting a hardened runway may unnecessarily complicate and hinder the mission due to force protection and confidentiality concerns.

Rhino LZ, due to its remote location, is an excellent example of where an SBA insertion should take place. Rhino was an excellent jumping off point for operations in the region and allowed for reasonable force protection costs. Unfortunately, it is unlikely given the current status of the C-17's semi-prepared runway capability that the SBA Bravo Echelon could have been delivered by the C-17 within the required time had this option been exercised.

This paper examines the limitations and outstanding issues which currently inhibit the ability of the C-17 to land on semi-prepared airfields in the magnitude required by the SBA mission. These limitations include, but are not limited to, premature failure of the semi-prepared surface, the inaccuracy of take-off and landing data (TOLD), and the inability to predict the number of passes possible on a semi-prepared runway. The intent of this paper is to provide an analysis of these issues and road map for the future which, when followed, should result in a more robust C-17 semi-prepared runway capability. This paper will also explore alternative concepts of operations and the use of other aircraft in the execution of the SBA mission and the impact these alternatives will have on the mission.

II. Literature Review

This nation has a unique capability to project power and force. No other nation in the face of the earth can do what we do, and it's because we have combination of airlift and tankers put together.

----- *General Ronald Fogleman, former Air Force Chief of Staff*

Introduction

There are three basic types of semi-prepared runways – matted, stabilized, and unstabilized. A matted semi-prepared runway is a runway of compacted indigenous material which has been overlaid with AM-2 aluminum matting to provide strength. A stabilized semi-prepared runway has received some type of treatment by mixing the top layer of indigenous soil with a stabilizing agent (cement, in most cases) to increase the bonding characteristics of the soil and therefore the weight bearing capacity of the runway. Runway stabilization is a difficult and time consuming requiring the ability to operate to exact engineering standards and at least 45 days for a minimum sized runway given current methods (McCann, 2002). An unstabilized runway is merely a runway made from the indigenous soil material which may have been graded and compacted.

Since the ability to land and sustain operations on both matted and stabilized runways has been demonstrated satisfactorily, this paper and chapter will focus primarily on the challenges associated sustained C-17 operations on unstabilized semi-prepared runways. The reason for the focus on unstabilized semi-prepared runways is the fact that these types of runways are the weakest link in semi-prepared runway operations. More importantly, unstabilized semi-prepared runways are the type most likely to be used during contingencies since it is unlikely that any time will be afforded for runway preparation prior to a contingency.

Strategic Brigade Airdrop 101

The SBA mission consists of two elements, the Alpha and Bravo Echelons. The Alpha Echelon refers to the actual airdrop of one Division Ready Brigade-Medium (DRB-M) which consists of 1 Division Assault Command Post, 1 Brigade Headquarters, 3 Airborne Infantry Battalions, 1 Aviation Task Force, 1 Immediate Ready Company, and 1 Division Support Command Element with support troops (Kasberg, 2001). The core component of the DRB-Medium is the 82nd Airborne Division rapid response capability located at Ft. Bragg, NC which may be tailored depending upon the mission with additional units from the 3rd Infantry Division's Intermediate Ready Company (IRC). In total, the SBA mission requires a total of 101 C-17s, 53 for the Alpha Echelon and 48 for the Bravo Echelon. Since the time-table may not allow any of the aircraft used in the Alpha Echelon to participate in the Bravo Echelon, the entire SBA mission could require as many as 101 mission capable aircraft. Of the Alpha Echelon sorties, 24 drop personnel, 22 drop heavy equipment (21 Dual Row), and one sortie drops container delivery system bundles (McWhorter, 2002). The 48 Bravo Echelon sorties carry the equipment noted in Table 1 (Kasberg, 2001) and include two sorties for a Tanker Airlift Control Element and for Crash Fire and Rescue assets. The Bravo Echelon delivers 4 M1 Abrahms tanks, 4 M2 Bradley Fighting Vehicles, 12 UH-60 Blackhawk Helicopters and, therefore, the combat power portion of the mission.

Table 1 SBA Personnel and Equipment by Echelon

Alpha Echelon	Bravo Echelon
2448 Troops	843 Troops
108 Wheeled Vehicles	179 Wheeled Vehicles
26 CDS Bundles	23 Pallets
18 Howitzers	16 OH5D Scout Helos
12 Engineer Repair Packages	12 UH60L Blackhawks Helos
6 Supply Platforms	4 M1A1 Abrams Tanks
	4 M2 Bradley Fighting Vehicles
	2 M113 Armored Personnel Carriers

In many cases, the objective of an SBA mission is an existing airfield seized by the Alpha Echelon. Four hours after the initiation of the airdrop, C-17s would begin delivering the Bravo Echelon by landing at the seized airfield. The closure time for the Bravo Echelon is 20 hours, hence 24 hours for the entire SBA mission. To close the mission in the designated time, a C-17 must land every 25 minutes for the full 20 hour period and the airfield must be large enough to handle four C-17s simultaneously. If the SBA objective is indeed a pre-existing airfield with a prepared runway and ramp, meeting the 20 hour time requirement would likely not be a problem. If, however, the objective is a single semi-prepared runway, the C-17 fleet would have severe difficulties meeting the 20 hour requirement for the Bravo Echelon insertion. Air Mobility Command arguably demonstrated the ability to deliver the Alpha Echelon when C-17s flew 12,000 miles non-stop from Pope AFB, NC to Kazakhstan and airdropped 500 82d Airborne Division troops on a drop zone in 1997. The ability of the C-17 to deliver the Bravo Echelon to a semi-prepared runway within the required timeline is undetermined.

The formal requirement for inserting the SBA Bravo Echelon into a semi-prepared airfield has been slow in its evolution. This formalization of the requirement began in 1998 when the Joint Integrated Concept Team (JICT) formulated an opinion which reads:

> The JICT determined that, while there were currently no documents which contained a specific written requirement to insert an SBA into a SAAF, the Defense Planning Guidance implies a requirement to be capable of such by its direction to provide a certain sized force anywhere within a defined timeline (Svisco, 1998)

The US Army formally outlined the requirement for executing the SBA mission into semi-prepared runways in a 2001 memorandum from the Chief of Staff of the Army General Staff to the Director of Plans and Programs for Air Mobility Command. In the memorandum, the Chief of Staff of the Army GeneralStaff:

> The XVIII Airborne Corps requires the ability to air-land combat, combat support and combat service elements on small austere airfields (SAAF). This requirement is taken from the Defense Planning Guidance that addresses the SBA and the guidance from the joint Integrated Process Team (IPT) formed in 1997 under the three-star level US Army and US Air Force Operations Staffs. (McChrystal, 2001)

The C-17 and Strategic Brigade Airdrop

Although the SBA mission existed beforehand, the development of the C-17 development program focused on the capabilities which make the C-17 ideal for the SBA. The ability to bypass intermediate staging bases (ISB) and deliver outsized cargo to small austere airfields (SAAFs) and semi-prepared runways became known in airlift circles as Direct Delivery and was one of the major selling points of the C-17 over competitors such as the military C-5 and the commercial Boeing 747. The requirement for an aircraft able to execute the SBA made the C-17 even more desirable and may have been the final straw in favor of a larger C-17 purchase after the initial purchase was capped at 40 aircraft. Regardless of the history, the present and future are put into perspective in a US Army memorandum on the C-17 semi-prepared runway capability and the SBA mission:

> With the retirement of the C-141 fleet, the load and distance limitation of the C-130, and the demands placed on the C-5 fleet, the C-17 is the only aircraft that can/will deliver the SBA within the requirements as specified in the DPG and recognized by the Department of the Army and Department of the Air Force. (McChrystal, 2001)

To ensure the capability of the C-17 to meet the demands of the SBA mission, the semi-prepared runway capability requires increased study and development.

Completed Semi-Prepared Runway Testing

The C-17's ability to land on unstabilized semi-prepared surfaces has been evaluated during different test events with the goal of releasing the capability for day-to-day operations. Following the capability release, on-going testing has made important discoveries, but the testing itself has been too limited to fully develop the capability to the level required.

Unpaved and Matted Runway Developmental Test & Evaluation (DT&E)

The Developmental Test & Evaluation (DT&E) program was conducted by the C-17 Combined Test Force at the Air Force Flight Test Center, Edwards AFB, CA from September through November 1994. This test program, which took place under authority of the Aeronautical Systems Center C-17 Systems Program Office, evaluated takeoff, landing and ground maneuvering on unpaved and matted runways. The unpaved runway testing was accomplished at Rogers Dry Lake, Edwards AFB, CA; Bicycle Lake Army Airfield, Fort Irwin, CA; Alamo Landing Zone, and Alamo, NV. The matted runway testing took place at the Marine Corps Air Ground Combat Center, Twenty-Nine Palms, CA.

Phase I Semi-Prepared Runway Operations (SPRO) Testing

The next substantial testing was Phase I Semi-Prepared Runway Operations testing conducted by the C-17 Systems Program Office from 1 April through 5 September 1997 at the locations in Table 2. This round of testing included 60 landings on 11 runways at six different landing zones (Tingle, 1998). The Phase I testing objectives were multifaceted.

Table 2 SPRO Phase I Locations

Name	Location	Climatic Conditions	Soil Type*	Soil Dry Density (pcf)			Soil Moisture Content (%)		
				in-situ	Opt	%	in-situ	Opt	%
Alamo LZ	Alamo, NV	Arid	SC/SW-SM	114.9	126.5	91%	6.2	10.3	60%
Bicycle Lake	Ft. Irwin, CA	Arid	CL	86.8	104.6	83%	9.8	20.5	48%
Rogers Lake	Edwards AFB, CA	Arid	CH	98.8	113.8	87%	5.1	15.6	33%
Holland LZ	Ft Bragg, NC	Humid	SP-SC	116.4			14.1		
Tyson LZ	Yuma, AZ	Arid	SC	109.8	120.5	91%	2.4	11.6	21%
Wilde-Benton LZ	Orogrande, NM	Arid	SM	112.3	123.7	91%	6.4	11.4	56%

Operationally, the focus of testing was to determine runway frictional characteristics, develop takeoff and landing planning guidance for dry and wet runways and to develop operational policy, tactics and procedures. The operational policy, tactics and procedures would build on lessons learned during DT&E and address takeoff settings, landing ground roll distances, ground maneuvering, engine-running offloads as well as maintenance procedures for pre-flight and post-flight inspections, technical order limitations and corrective actions.

From an engineering aspect, the goal of Phase I SPRO testing was to develop and expand on the knowledge base regarding the design, evaluation and maintenance of runways to support C-17 semi-prepared runway operations. Specifically, engineers needed to determine the minimum-sized runway, how to design an airfield to support C-17 operations, how to predict whether or not and for how many passes an existing airfield could support C-17 operations and how to best maintain semi-prepared airfields for continued use. The difficulty of these tasks are addressed in subsequent sections of this paper.

In addition to formal test regimes, pertinent test data has been gathered and studied following various training and exercise missions independent of formal test programs where the scenario called for landing on unstabilized semi-prepared airfields.

AM-2 Aluminum Matted Runways

The ability of AM-2 matted runways to support C-17 operations was initially tested at the Marine Corps Air Ground Combat Center (MCAGCC) in Twenty-nine Palms, California during DT&E in September 1994. The objectives of the testing were to evaluate the ability of the C-17 to operate on the Strategic Expeditionary Landing Field (SELF - 8,000 feet by 150 feet) and the Expeditionary Air Field (EAF 2000 – 3,840 feet by 72 feet) carrying up to 160,000 of cargo and enough fuel to fly 300 NM following offload. These requirements are outlined in the C-17 Operational Requirements Document (Fucci, 1993).

The AM-2 Aluminum matting Tests determined that the C-17 was able to land, takeoff and perform necessary ground operations on both the SELF and EAF runways at the gross weights required by the Operational Requirement Document. The ability of AM-2 matting to structurally support the C-17 was deemed adequate following post-test review of the stress data collected by engineers from the Naval Air Warfare Center at the Lakehurst Naval Air Station in Lakehurst, NJ (Bouras, 1995). However, since the sub-grade at Twenty-nine Palms had a CBR in excess of 50, the ability of AM-2 matted runways with sub-grades less than 50 cannot be determined without further testing.

Stabilized Semi-Prepared Runway Evaluations

The ability of the C-17 to land on stabilized semi-prepared airfields has been proven numerous times on cement-capped runways at the Joint Reserve Training Center (JRTC) at Ft Polk, LA. The JRTC has three stabilized runways which were originally built for C-130s and subsequently upgraded to meet C-17 standards. The upgrade required a 10 inch cap which was 3-4% common Portland cement. The main cement capped runway, Geronimo ALZ has sustained over 100 C-17 landings (over 200 passes) with loads up to and including M1 tanks without requiring maintenance on runways, taxiways, or ramps (McCann, 2002).

Unstabilized Semi-Prepared Runway Operational Challenges

Since the SBA Bravo Echelon insertion is the most demanding scenario involving semi-prepared runway operations, the following section discusses the challenges to the C-17's ability to support this mission. In order to fuse academic thought and operational experience, this discussion works within the framework of the entire range of testing and operational experience gathered to date including the experiences gained during recent operations at Rhino LZ.

Some of the challenges to sustained operations on unstabilized semi-prepared runways are obvious and can be mitigated by altering procedures. Other issues require further study and analysis and possibly alternative concepts of operations designed to reduce the impact of repeated operations on the runway.

One of the main problems inherent with landing a 450,000 pound aircraft on dirt is obviously the inability of unstabilized semi-prepared runways to support the weight of the aircraft without the surface shearing, or breaking up. When the aircraft wheels break through the top layer of the runway surface numerous potential problems arise from the liberated soil and its interaction with the aircraft. Most of the problems are associated with, but not limited to, rutting of the runway, loose till creation, dust clouds, foreign object damage (FOD), and uncertainties in takeoff performance.

Airfield Rutting

The term rutting describes the situation where the force exerted by the aircraft wheels compacts the soil directly under the wheel path causing an upheaval of material on either side of the wheel. In simple terms, rutting describes the impressions the tires make on the ground, the most important characteristic being the depth of the rut. From an engineering aspect, a runway surface is considered failed when the depth of these ruts reaches 3 inches (Tingle, 1998) although the C-17 operated on semi-prepared runways with 18 inch ruts at Rhino LZ (Williamson, 2002). When the ruts hinder safe operations, runway maintenance is required prior to subsequent takeoffs and landings. The extent of the maintenance depends upon the equipment available, the time available and the extent of the damage. Runway maintenance interrupts the flow of aircraft and thus reduces total airfield throughput proportionate to the time required to perform the maintenance. The requirement for runway maintenance also means that a number of sorties commensurate with the amount of equipment and personnel must be earmarked to airlift or airdrop road graders, loaders, bull-dozers, and rollers. At Rhino LZ, Navy Seabees from the Naval Mobile Construction Battalion 133 repaired the runway following nightly C-17 missions to prepare the dirt strip at Rhino LZ for the following night's missions. Most of the time, the Seabees used graders brought in on the first C-17 missions to scrape the rutted layer of dirt off in order to expose the relatively undamaged subsurface for the next night's flying schedule. Lieutenant Commander Cooke, of Naval Mobile Construction Battalion -133 described the first landing after Seabee runway maintenance as "a pretty good ride" but indicated that "everybody else had to pay the price" of rutting from previous aircraft (Sawyer, 2002). After digging a barrow pit and finding some clay-like soil, the Seabees were able to use it on the most critical parts of the runway (Lammond, 2002). Even then, the repairs only lasted for 4 to 5 days before they required rework (Cooke, 2002). During this operation, the flow of aircraft was not interrupted since aircraft were only scheduled at night at half-hour intervals. An around-the-clock operation would certainly have been put on hold for runway maintenance.

A new phenomenon associated primarily with the C-17 is the greater tendency for rutting during the braking portion of an assault landing than during the actual touchdown. According to Tingle:

> "At all of the unsurfaced test sites, it was observed that the maximum damage to the surface of the runway occurred during the braking of the aircraft during landing operations. The braking zones of the runway possessed the worst rutting. The touchdown zones exhibited minor rutting, while the taxiing zone consisted of the least severe rutting." (Tingle, 1998)

Further testing determined that the C-17 causes 2.5 times more damage while braking on a semi-prepared surface than it does during normal taxi operations. During discussions with personnel present at Rhino LZ, it was evident that this phenomena was repeated when the parts of the runway that failed most rapidly were the touchdown and braking zone (Cooke, 2002).

The C-17 Technical Order recognizes this tendency for the C-17 to cause increased damage to semi-prepared runways. The Performance Manual of the C-17 states that, "Figures 10-4 and 10-5 (the CBR charts) are not recommended for landing operations where maximum effort braking may be utilized. The runway degradation on semi-prepared airfields are highest with maximum effort landings…" (Boeing, 1999). The only procedural initiative designed to reduce rutting has been the reduction of the main landing gear tire pressure from 145 to 114 (+/- 5) psi and the nose gear tire pressure from 155 to 103 (+/- 5) psi in order to distribute the aircraft weight over a larger surface area and increase tire buoyancy. However, due to limitations set by the manufacture of the tires, this procedure limits the C-17 maximum gross landing weight to 435,000 lbs as opposed to the normal maximum landing gross weight limitation for semi-prepared runways of 447,000 lbs. This limitation poses its own unique set of issues which are discussed in later sections.

Loose Till

Closely related to and a byproduct of rutting is loose till generation which is a term that describes the build-up of pulverized surface material in conjunction with continued semi-prepared runway operations. A report on Phase I SPRO Testing notes that, "The development of this loose material increased rapidly with aircraft passes.

However, after several landings of the aircraft the depth of the loose soil layer (loose till) seemed to stabilize at a constant depth for each airfield" (Tingle, 1998). Upon further discussion with Mr. Tingle, he revealed that although the depth of the loose soil layer does not stabilize, the rate at which new loose material is generated stabilizes at a much lower rate than that at which the loose soil layer was initially generated at the onset of operations (Tingle, 2002). While the loose till appears to provide some protection for the compacted layer beneath, it also results in additional friction between the runway and aircraft wheels during takeoffs and landings. Since this added friction results in longer takeoff rolls, it must be accounted for during takeoff planning to ensure the ability of the aircraft to takeoff in the available amount of runway. The added friction is expressed during takeoff calculations as Rolling Friction Factor (RFF). Loose till up to 3.25 inches has been assigned an RFF value as depicted in Table 3, but the effect of loose till in excess of 3.25 inches has not been ascertained.

Table 3. Loose Till to RFF Correlation Chart

Loose Till Depth	Rolling Friction Factor
0 to 1.0 inches	5
1.1 to 2.0 inches	10
2.1 to 2.5 inches	15
2.6 to 3.25 inches	20
>3.25 inches	Maintenance Required

At lower gross weights, RFF has a minimal effect on takeoff ground rolls from semi-prepared runways. According to Table 4, the difference between the takeoff roll of a C-17 weighing 320,000 lbs (aircraft plus 40,000 lbs of cargo and/or fuel) with an RFF 20 (2.6 to 3.25 inches of loose till) is only 150 feet longer than the same aircraft taking off with an RFF of 2 (No loose till). The RFF is more of a factor at heavier gross weights where the difference between the takeoff roll of a 450,000 lb aircraft taking off with RFFs of 20 and 2 is 1360 feet. Most of the time this difference will not become a factor since aircraft land heavy and takeoff at lighter gross weights after off-loading cargo during a contingency.

Table 4. RFF Adjusted Takeoff Ground Roll

RFF	320	340	360	380	400	420	440	450
2	1430	1550	1760	1980	2220	2480	2760	2900
5	1430	1570	1800	2050	2310	2600	2910	3080
10	1450	1630	1880	2160	2460	2790	3150	3350
15	1480	1670	1930	2220	2550	2940	3380	3630
20	1580	1840	2130	2480	2890	3370	3940	4260

However, one must think of the added effort required to ride a bicycle through sand to realize that large amounts of loose till could possibly result in some major increase in the takeoff roll of even relatively light-weight aircraft.

Foreign Object Damage (FOD)

Jet aircraft engines are very sensitive to the ingestion of any hard objects such as rocks, etc. These small items, referred to foreign objects can cause substantial damage to the turbine blades found in jet engines; damage which can result in compressor stalls, poor engine performance, as well as turbine blade and thus engine failure. Damage which results from these small items is called foreign object damage (FOD). Although the C-17’s engines are mounted over 8 feet from the ground, there is still danger of FOD ingestion due to the large amount of suction created by the turbines when running at high speeds. This suction often creates a high-speed rotating funnel of air called a vortex during C-17 ground operations. These vortices are especially prevalent during aircraft backing operations under high thrust requirements. On at least one occasion this vortex lifted a manhole cover from the ground while the aircraft was performing backing operations.

The size of the aggregate making up the runway also factors into the risk assessment associated with FOD for a given runway. Runways consisting of aggregate sizes greater than 1.5 inches have a very high risk of FOD ingestion while runways with aggregates measuring ¾ inches to 1.5 inches pose high risks and aggregate less than ¾ inches pose moderate risks. Overall, semi-prepared runway operations as a whole carry "high" risk assessments for FOD damage. During Phase I SPRO Testing at Wilde Benton LZ, test operations were suspended on two separate occasions when the engines on the test aircraft sustained FOD requiring extensive repairs.

FOD is not limited to the aircraft engines. During testing and in subsequent real-world operations, FOD damage has been sustained primarily to the underside of the aircraft by rocks launched by the nose or main landing gear tires. During initial testing, the rotating beacon located aft of the nose wheel consistently sustained damage ranging from cracked lens covers to the loss of the entire fixture (Bouras, 1995). Communications antennae are also frequently damaged and require replacement following landings on semi-prepared runways as documented in field reports from Afghanistan. Some types of damage can be reduced through the use of Teflon protective tape applied to the equipment most likely damaged by FOD. During contingency missions to Afghanistan during Operation ENDURING FREEDOM at least one C-17 sustained damage to landing gear wheel and brake assemblies (Papetti, 2002) caused by the buildup of dirt and mud. This buildup prevented the brake and wheel assemblies from rotating freely and resulted in cracked brake discs. Ten of the twelve wheel and tire assemblies as well as all twelve brake assemblies were replaced to correct the damage. Main landing gear doors, which are made of composite materials, have also sustained semi-prepared runway related damage (Shoup, 2002).

Dust

Dust is another major concern during semi-prepared runway operations. During semi-prepared runway testing, dust clouds which enveloped the aircraft following landing resulted in numerous problems. The large amount of dust ingested by the aircraft engines spilled over into the air conditioning packs and the resulting dust storm was so sever as to limit visibility – inside the cockpit. Operating with the air conditioning packs and engine bleed valves closed reduced most problems associated with dust inside the aircraft and the environmental system. However, the lack of bleed-air to the air conditioning system by itself, or coupled with dust-clogged filters can result in inadequate cooling for the avionics resulting in degraded avionics performance in hot and/or humid climates. In addition to being tactically undesirable since they can literally be seen for miles, dust clouds as large as those which the C-17 can generate can momentarily blind air and ground crews causing safety concerns.

There are some techniques to reduce dust, but few are viable for contingency missions since most involve mechanical stabilization by mixing the top layer of the runway with a stabilization medium. For contingencies, the most viable method for containing dust in the absence of water is the use of chemical dust palliatives which can be mixed with the dirt, or in a contingency, sprayed on. A report on dust palliatives (Jeb S. Tingle, 1999) lists over 70 potential products grouped in five categories: (1) salts, (2) organic non-bituminous chemicals, (3) petroleum-based binders, (4) polymers, and (5) chemical and biological stabilizers (acids and enzymes). While many products have shown potential as dust inhibitors, their success depends upon the soil type and climatic conditions. At Rhino LZ a dust inhibitor was badly needed since the indigenous soil had moon dust-like consistency when pulverized. A commercial product, Enviro Tac, was hurriedly readied and shipped to Rhino LZ and proved successful under local conditions.

Takeoff and Landing Data (TOLD)

A hint of the problems with TOLD for semi-prepared runway operations can be found in the notes, cautions and warnings of Appendix B of the C-17A performance manual (Boeing, 1999). Appendix B contains TOLD for C-17 semi-prepared runway operations. A sample reads:

NOTE

> The performance data in this appendix apply reduced safety margins to achieve maximum performance, and should not be used for normal operations. The takeoff data listed in Figures B-8 through B-42 does not consider V_{MCG} directional control limitations. In addition, the data in Figures B-43 through B-49 assumes all four engines are placed in maximum reverse thrust to achieve the charted landing distance. Do not use the data from this appendix without operating command approval.

WARNING

> Semi-prepared runway operation has inherent risk due to uncertainty/ variability in the runway conditions. If an inaccurate RFF is reported to the pilot, takeoff data will be incorrect. If an accurate RFF is used, engine failure may result in the inability to safely take off within the runway available.

WARNING

> Ground Minimum Control Speed, (V_{MCG}), for concrete runway operations was used for this data. V_{MCG} performance for semi-prepared operations

has not been determined. Therefore, continued accelerations after engine failure may result in lateral departure from the runway.

Most will agree that the Runway Friction Factor needs to be re-visited. The accuracy of this correction factor requires further study and is questioned in a U.S. Army, XVIII Airborne Corps memorandum:

> Current data does not allow accurate determination of runway length requirement for wet surfaces. Runway Condition Ratings (sic Readings) and Rolling Friction Factors (RFF) are based on surface friction. Current measurement methods must be refined to allow construction units and Air Force Special Tactics Teams (STT) to accurately determine minimum runway lengths for a full range of moisture/wetness conditions

Air mobility officials acknowledge the requirement for additional "refinement" of the RCR and RFF measurement methods in inter-office emails between Air Mobility Command Officials (AMC/XP, 1999). The RFF value is critical when planning runway lengths as extremely high RFF values can result in increased takeoff rolls. Operationally, pilots flying into Rhino LZ reported noticeable hanging up and momentary pauses in acceleration when steering the aircraft through soft spots in the runway during the takeoff roll. However, the same pilots reported no significant increase in the length of the takeoff roll since their aircraft were not heavily loaded. By the same token, the loose till definitely assists in stopping the aircraft since pilots also described the absence of the need to apply braking to slow the aircraft at Rhino LZ after the field had been softened by previous aircraft operations.

Field Code Changed

In addition to the problem with RFF, the calculated stopping distance on wet runways demandss refinement. The friction coefficient for capturing the runway condition is the runway condition reading, or RCR. The RCR value for dry semi-prepared runways is 20, compared to 23 for dry paved runways. The RCR for most wet paved runways RCR is normally 13 but aircrews currently calculate the landing distance for wet semi-prepared runways using an RCR of 4, the same used for icy paved runways. The normal (RCR 20) landing distance of a 447,000 lb (max gross weight for semi-prepared runway operations) C-17 is increased from 2,930-feet at sea level on a standard day to 5,370-feet using full max braking and max reverse thrust during wet runway operations. In addition, the runway length required for a 320,000 lb (empty weight + @ 2 hours fuel) airplane on a dry semi-prepared runway (RCR 20) increases 1,000-feet when operating on a wet semi-prepared runway (RCR 4) due to rejected takeoff considerations.

The TOLD issues carry serious safety implications if not adequately refined since errors could potentially result in an aircraft mishap. Rhino LZ had almost 7,000 feet of runway and therefore more than adequate runway for takeoffs and landings especially since conditions remained dry throughout Rhino LZ operations. In future operations, the use of shorter semi-prepared airfields may be required; adequate takeoff, rejected takeoff and landing data will be critical.

Operational Limitations

During multiple scenarios calling for the C-17 to operate on semi-prepared runways the C-17 will be called on to carry near maximum loads given the 447,000 lb gross weight limitation for semi-prepared runway operations. One example of such a scenario in addition to the SBA Bravo Echelon involves the deployment of the Immediate Readiness Company (IRC) which can be enroute to any worldwide location within 22 hours. The IRC consists primarily of 4 M1A1 Abrams tanks and 4 M2A2 Bradley Fighting Vehicles and is designed to deploy on eight C-17s, the only aircraft capable of delivering the M1A1 to a semi-prepared airfield. The 447,000 lb restriction on semi-prepared runway operations limits the flexibility of C-17s carrying M1A1s into semi-prepared runways because the combined gross weight in addition to operational considerations leaves little room for fuel. The combined gross weight of the C-17, the M1A1 (including ammunition and 3/4s of a tank of gas), and overhead fuel leaves room for less than one hour of flying time worth of fuel based on a 20,000 lb fuel burn for takeoff and climb to enroute altitude. Table 3 displays a visual representation of this fuel calculation (Kuska, 2000).

Table 5. C-17 with M1A1 Fuel Calculation

447,000	C-17 Max Gross Weight for SPR Ops
-280000	C-17 Operating Weight
167,000	Usable cargo and fuel weight
-136400	Combat-Ready M1A1
30,600	Max fuel weight
-16000	Required Overhead Fuel
14,600	Usable Fuel

While this fuel limitation is not insurmountable, it does require additional planning and coordination which requires fuel to be available at the target airfield, via an aerial refueling tanker, or at another airfield within the available flying time given the limited amount of fuel on board after offload. All of these options require additional planning, coordination, manpower, and assets.

Runway Bearing Strength Measurements

There are various ways to classify the strength or bearing capacity of a runway dependant upon the type of surface being classified. According to the performance section of the C-17 Technical Manual, (the -1-1) the method used to classify the strength of semi-prepared runways is the California Bearing Ratio (CBR) which expresses strength in terms of a percentage of the bearing strength of crushed rock (Technical Order 1C-17A-1-1). A CBR value can be obtained by using the field dynamic cone penetrometer (DCP) test. The dynamic cone penetrometer consists of a 0.625 inch diameter steel rod with a steel cone attached to one end which is driven into the subgrade by means of a sliding hammer. Measurements, which indicate how resistant the subgrade is to penetration by the steel rod, are then converted to a CBR value using the equation $CBR = DCP^{1.12}$ where DCP is the penetration distance in millimeters per hammer strike.

California Bearing Ratio

Once the CBR is determined, this value is then used to predict the ability of a semi-prepared runway to handle different traffic volumes. The C-17 technical order chart used for converting CBR to semi-prepared runway suitability indicates that the minimum CBR value for a runway which can support one C-17 operation is approximately 9.0, or 9.0% of the weight-bearing capacity of crushed rock. The chart also indicates that 50 C-17 operations on a runway would require a CBR value of 14.5 and 100 operations would require a CBR value of 17. For comparison, most natural uncompacted surface soils range in CBR strength from 3 to 8. It should also be noted that the CBR strength changes with moisture fluctuations, and the landing zone may not meet the strength requirements immediately after periods of heavy precipitation.

All airfield design within the United States and completed by U.S. agencies is based upon the CBR design method. The use of CBR values have been used extensively in the design of both permanent and semi-prepared airfields. However, the airfield design and evaluation criteria or guidance using the CBR was originally based upon rolling-wheel traffic. Slow rolling traffic is generally more damaging to a permanent pavement due to the long duration of the load impulse and full burden of the aircraft's load (under zero lift conditions). During the Phase I SPRO testing of the C-17 aircraft under live-flight conditions, the airfield surface deteriorated in a different manner than the original pavements used to develop the design and evaluation criteria. The airfield surface sheared under relatively low amounts of aircraft traffic resulting in rutting and the development of loose surface till. Since the CBR method was not based upon this type of deterioration, the design and evaluation curves previously developed have been less successful in determining the ability to support operations of the C-17 on semi-prepared runways. The original design and evaluation guidance is still valid for taxiing operations as they are representative of rolling-wheel traffic.

Tingle (Tingle, 1998) agrees that surface CBR values cannot successfully predict the runway performance for the C-17 aircraft under the operating conditions of the Phase I SPRO test program. This tendency was borne out during operations in Afghanistan when prior to operations at Rhino LZ, the initial surface CBR value was 72. This left Air Force Combat Controllers "cautiously optimistic that it would support C-17s" (Sawyer, 2002). While the C-17 performance manual indicates this would support hundreds of C-17 passes based upon the "rolling-wheel" criteria, (SPO, 1997) the field required extensive maintenance following only eight landings.

The rolling-wheel criteria does not account for the increased loading from the impact of an assault landing, or in the case of the C-17, maximum braking actions. As noted, the C-17 performance charts (AFCESA/CES, 97) convert CBR to predicted passes, meaning rolling passes, and are of little use in predicting the utility of a semi-prepared runway for sustained C-17 operations on unsurfaced airfields, especially landing operations involving maximum, or near maximum braking.

Predicting Semi-Prepared Runway Behaviors

Predicting how a semi-prepared runway will respond to the forces present during C-17 operations is a difficult proposition. The ability to support the weight of a 447,000 lbs aircraft pounding the runway with a descent rate of 360 feet per minute is a complicated matter since it involves, but is not limited to, the inherent soil strength, the friction characteristics between the soil and the tire, the actual time of loading which is based on the speed and braking of the aircraft and the wheel load and tire pressure (Jeb S. Tingle, 1999). In addition, these forces are constantly changing based on factors such as the diminishing effect of lift and pilot reaction, to name a few. This inability to predict the number of operations a semi-prepared runway will support is probably the major shortcoming of the entire semi-prepared runway operations arena. If this predictability could be assured, planners would know exactly which airfields world-wide could support the SBA mission. Since relatively little testing has been accomplished compared to the task at hand, the available database is small. While the strategic brigade airdrop calls for over 40 landings possibly on a single semi-prepared runway, the highest frequency of C-17 landings ever documented on a single unsurfaced semi-prepared runway without maintenance was during Phase I SPRO testing when ten landings were recorded at Bicycle Lake LZ and Tyson LZ where rut depths exceeded 7 inches. To plan for a strategic brigade airdrop scenario, planners will have to determine based on a combination of indigenous soil types and climatic conditions whether a proposed target airfield can support planned operations. An incorrect assessment could risk mission failure, or worse, an extreme loss of life since the airland portion of the Strategic Brigade Airdrop delivers the heavy combat fire required by the troops on the ground for force protection and long term operations. Emerging technologies such as satellite imagery and remote assessment systems can assist in determining moisture levels and soil type composition but the database is too small to accurately model how locations with known moisture levels and soil composition will behave in a scenario as demanding as strategic brigade airdrop mission. According to engineers studying the problem, data from at least 40 passes on the same runway would be needed to build a reliable model (Tingle, 2002).

The Nature of Dirt

A large part of the difficulties in modeling dirt is the nature of dirt itself. Dirt can be classified in many ways according to many different characteristics which affect its ability to function as a semi-prepared runway surface. The American Society of Testing and Materials (ASTM, 1995) classifies soils according to the Unified Soil Classification System (USCS) which categorizes soils based upon specific engineering properties designed to predict how soil types will perform as construction materials. After initial

Table 6. Soil Groups

Soil Groups	Symbol
Gravel	G
Sand	S
Silt	M
Clay	C

classification as coarse-grained, fine-grained, or organic, each type of soil is assigned a two letter symbol identifying its basic composition and qualities. The first letter of the identifying symbol describes whether the basic composition of the soil is gravel, sand, silt, clay, or any combination of the four according to Table 6. The second letter

Table 7. Soil Characteristics

Soil Characteristics	Symbol
Well Graded	W
Poorly Graded	P
High compressibility	H
Low compressibility	L
Organic (peat)	Pt
Organic (silt and clays)	O
Liquid limits under 50	L
Liquid limits over 50	H

describes the soil characteristics according to Table 7.

While there are tests which can determine the exact properties of soils, many are time consuming and require an actual sample of the soil material. This is not practical for an SBA scenario. When considering the different soil types and then the tendency for soils to exhibit different characteristics under different levels of moisture content, the difficulty of predicting the ability of a runway to support semi- prepared runway operations in the absence of hands-on testing becomes readily apparent. Table 8 graphically depicts the breakdown of soil types and soil type combinations present worlside.

As stated previously, one of the objectives of Phase I testing was to develop and expand the knowledge base engineers possessed on the design and maintenance of dirt runways. To do so, engineers from the Waterways Experiment Station studied the dirt types present during Phase I testing in order to evaluate how it performed under the stress

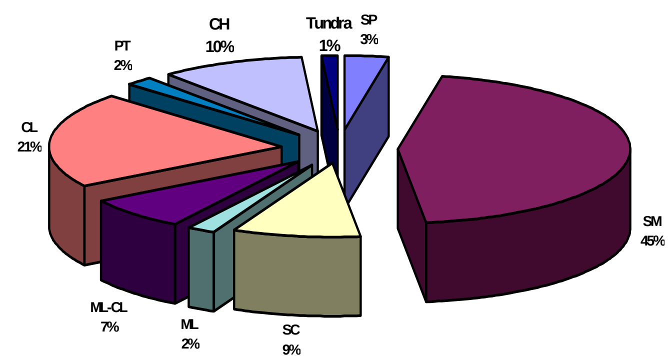
Table 8. Soil and Soil Combination Types

Major			Symbol	Field Identification (Base fractions on estimated)		
Coarse-grained More than half of material is larger than No. 200 sieve	Gravel More than half of coarse fraction is larger than No. 4 sieve	Gravels <5% Fines	GW	Wide range in grain sizes, all intermediate sizes substantially represented		
			GP	Predominantly one size or some intermediate sizes missing		
		Gravels >12% Fines	GM	Nonplastic fines or fines with little plasticity (see ML below)		
			GC	Plastic fines (see CL below)		
	Sand More than half of coarse fraction is smaller than No. 4 sieve	Sands <5% Fines	SW	Wide range in grain sizes, all intermediate sizes substantially represented		
			SP	Predominantly one size or some intermediate sizes missing		
		Sands >12% Fines	SM	Nonplastic fines or fines with little plasticity (see ML below)		
			SC	Plastic fines (see CL below)		
Fine-grained More than half of material is smaller than No. 200 sieve				Identification on Fractions smaller than No. 40		
				Dry Strength	Wet Shake	Thread or Ribbon
	Silts & LL <50		ML	None to slight	Quick to slow	None
			CL	Medium to high	None to very slow	Medium
			OL	Slight to medium	Slow	Slight
	Silts & LL >50		MH	Slight to medium	Slow to none	Slight to medium
			CH	High to very high	None	High
			OH	Medium to high	None to very slow	Slight to medium
Highly Organic			Pt	Readily identified by color, odor, spongy feel, and frequently by fibrous texture		

of C-17 semi-prepared runway operations. Although Phase I testing involved dirt types Clay and Sandy Clay and those two types of soils are found over 30% of the world (See Figure 1) the test data only applies to an estimated 6.9% of the earth's surface since Phase I testing only tested CL (Low-Plasticity Clay) and SM-SC (Clayey Silty-Sand) soils in ***arid/semi-arid climates***. Testing of Clay and Clayey Silty Sand soils in arid/semi-arid climates is critical since these soils lack the moisture necessary in arid/semi-arid climates for compaction and cohesion. Thus, these materials tend to break down relatively easily under high stress conditions. Many of the potential objectives of a forced entry scenario could also lie within arid/semi-arid climates with indigenous soil types similar to those tested during Phase I. In those scenarios, the deterioration models developed under the Phase I SPRO program should be applicable.

Additional testing will be required to assess the performance of these and other types of soils under different climatic conditions. This is one of the central difficulties encountered during semi-prepared runway research since test results for a given soil type under a given moisture level do not apply to the same soil type under different levels of moisture. In fact, additional testing on a different soil type in a humid temperate environment has demonstrated the inadequacy of the existing models designed to predict runway failure (Tingle, 2001)

Figure 1. World Soil Types



Modeling

Engineers at the Waterways Experiment Station have met with minimal success when attempting to formulate models to predict the performance of semi-prepared runways based on existing test data. Following Phase I testing, the engineers at the Waterways Experimental Station built a model for predicting the amount of loose till generated during C-17 landing operations (Tingle, 1998). In a later report, (Jeb S. Tingle, 1999), a model was generated using data from Phase I testing which modeled the depth of ruts created by C-17 operations on semi-prepared runways. The engineer primarily responsible for building the model quickly points out that the models are valid only for the combination of extremely dry climates and the soil types present at the runways used during Phase I SPRO testing (Tingle, 2002). The engineer also points out that the models are not valid for operations exceeding 10 landings since that is the highest number of landings recorded during test observations as discussed earlier.

In summary, while these models have been shown to be predictive in nature for limited operations in a certain type of dirt under certain climatic conditions and moisture levels, they have also shown that each type of dirt must be tested under each specific condition to provide data which could be used in a model valid for all types of soils, moisture levels, etc. The inability of the existing models to be predictive for other climate/soil type combinations was proven demonstrated an Emergency Deployment Readiness Exercise (EDRE) at Rhine-Luzon ALZ, Camp Mackall, NC.

During the EDRE at Rhine-Luzon, 8 C-17s loaded with equipment from an Immediate Readiness Company (IRC) performed five landings on Runway 27 and three on Runway 09. The average weight of the aircraft was 431,000 lbs with an average payload of 126,000 lbs. These aircraft operated with standard tire pressures, not the reduced tire pressures sometimes used for semi-prepared airfield operations. The runway at Rhine-Luzon exhibited lower CBR strengths as measured by DCP testing although it was composed of an SP-SC soil type similar to those studied during Phase I SPRO testing. The combination of higher tire pressures and low runway bearing capacity would lead one to predict that the runway at Rhine-Luzon would not perform as well as those tested during Phase I Testing. In actuality, the Rhine-Luzon fared better since minimal rutting and loose till occurred during the eight landings. The difference in performance was primarily attributed to additional internal soil cohesion characteristic of clay materials in humid environments. In other words:

> These figures reveal that the existing model over-predicts the rut depths for the operation conducted at Rhine-Luzon ALZ. Furthermore, despite the fact that the soil strength were lower than those measured at the Phase I test sites, the magnitude of the rutting was much less…The figures clearly indicate that the original model developed for the Phase I test sites is inadequate to predict the amount of rutting for the soil type and climate of Rhine-Luzon ALZ…the fact that very little loose till was generated in 8 landings indicates that the loose till model is inadequate for describing the deterioration of the soil type and climate of the current ALZ…It should be re-emphasized that the Phase I rut and loose till models are valid only for the soil types and climate of the Phase I test sites. (Tingle, 2001)

Although these conclusions come after only eight landings (five on the same surface), it is clear that one cannot extrapolate when considering soil type and climate conditions other than those for which the model was built and from which the data was recorded. This clarifies the need for additional testing. It also re-emphasizes once again that the original "rolling-wheel" CBR criteria can be deceptive if used solely to determine the actual ability to sustain C-17 semi-prepared airfield operations since in this case, an airfield with a low CBR value out-performed multiple airfields with higher CBR values.

III. Research Method

This research paper brings together pertinent information from various points of view to provide a comprehensive look at the C-17 semi-prepared runway operations capability. In order to provide this comprehensive look, the research method involved various types of media ranging from written works, magazines, journal articles, reports, theses, internet sites, government resources, aircraft technical manuals, email communications, briefings, and telephone interviews.

While there were no formal questionnaires, a good deal of information concerning current and/or recent operations came from telephone interviews with experts -- some with recent operational experience. This information was invaluable in confirming and corroborating information gained from written sources. It is possible that some sources may have had some biased interest in the outcome of this paper, or in some other aspect of the C-17 semi-prepared runway capability, which could have possibly lead to questions in information validity and bias. However, I found very little information which contradicted other written sources. In the case of personal communications, I was able to confirm information gained through telephone interviews, or emails usually from at least one additional personal communication and many times from multiple sources. Thus, I am confident about the viability of the information sources used to compile the information in this paper.

IV. Analysis

The critical elements of deterrence are our conventional warfighting capabilities: forces and equipment strategically positioned, our capability to rapidly project and concentrate military power worldwide…

---National Military Strategy of the United States

The review of literature revealed that the C-17 can, indeed, land on semi-prepared runways. What has not yet been demonstrated is the ability of the C-17 to land on the same semi-prepared runway more than ten times and certainly not the 48 times required by the SBA scenario. There are three major issues which stand as stumbling blocks which currently prevent the C-17 from demonstrating the ability to insert the SBA Bravo Echelon within the required time. While issues such as FOD and dust can be either mitigated through procedure or accepted as the risks inherent with landing on dirt, these three major issues must be resolved before the C-17 can demonstrate the ability to perform the full range of SBA scenarios. The National Military Strategy of the United States indicates that, “Deterrence rests in large part on our ***demonstrated*** (italics added) ability and willingness to defeat potential adversaries and deny them their strategic objective”. The ability to demonstrate the ability of the C-17 to deliver the Bravo Echelon to a semi-prepared runway is critical if the deterrent capability of the SBA is to be maintained. The three issues requiring resolution are the undemonstrated ability of an un-stabilized semi-prepared runway to support sustained operations without requiring maintenance; the inability to accurately predict the number of landings an unstabilized semi-prepared runway could support; and the inaccuracy of TOLD computations for takeoffs and landings, especially under wet conditions.

The Undemonstrated Ability to Deliver the Bravo Echelon into a Semi-Prepared Runway Without Requiring Maintenance

The first issue is not only the most obvious, but will require the greatest effort to resolve, as well. The ability to deliver the SBA Bravo Echelon has not been demonstrated, yet a major part of our deterrent strategy depends upon it. Phase I SPRO testing, while limited in scope, provided a glimpse into the difficulty a semi-prepared runway may encounter trying to support 48 landings. For example, on Runway 17 at Tyson ALZ, the DCP-generated average CBR values at depths of 6”, 12”, 24”, and 36” were 50, 43, 42, and 30 respectively. Twenty-six operations, which included six landings, 10 taxi operations, and 10 takeoffs, resulted in a maximum of 6.0 inches of loose till and 6.4-inch ruts. Tingle indicated that, “…after several landings of the aircraft, the depth of the loose soil layer seemed to stabilize at a constant depth…” (Tingle, 1998). Upon further discussion with Mr. Tingle, he indicated that the rate of deterioration of the runway surface increases initially and then decreases to a somewhat constant level (Tingle, 2002). It would seem in this case that the loose soil to a certain extent absorbed the punishment and protected the subgrade . One could hypothesize from this information that the loose till depth would stabilize and act to protect the strength of the subgrade and that therefore operations could continue for much longer than anticipated as long as the aircraft could maneuver in the stabilized layer of loose till. In reality, the answers to these questions are still unknown since testing has been too limited. Without testing, it is a long leap of faith to conclude that the ability to safely perform 6 landings and 26 total operations extends to the ability to perform 48 landings and as many as 144 operations (In the absence of a parallel taxiway each of the 48 airplanes would land, back taxi, and takeoff on the same runway) without any runway maintenance which would interrupt the flow of aircraft.

There are still many questions left to answer. If the runway does require repair in the middle of operations, what is the best way to repair the runway? What type of equipment is required? How much manpower is required? What materials work best? How many subsequent operations will a newly repaired runway support prior to the next round of repairs? Does the runway performance degrade with each subsequent repair cycle until you have to shut it down for an extended period of time? These questions remain unanswered due to the limited amount of testing accomplished during Phase I SPRO Testing. At Rhino LZ Navy Seabees had the luxury of time to repair the runway since flight operations took place at night only. Even the repairs made with clay-like soil lasted only 4-5 days (approximately 8 C-17 landings and 16 additional operations per day) before again requiring maintenance. To complicate matters, the answer for each of the previous questions may vary depending upon soil and climate combination.

Predicting the Behavior of Semi-Prepared Runways

This leads to the second major issue– that of predicting runway performance based solely upon soil type and climate. This is a must-have capability. Even if the semi-prepared runway capability is fully developed and demonstrated, the inability to predict the number of passes a potential semi-prepared runways would allow unnecessarily constrains commanders considering SBA as a course of action. While under-estimating would not be a problem, underestimating would prove problematic since this would have over-predicted the number of possible passes.

Takeoff and Landing Data for Semi-Prepared Runway Operations

The utility of any semi-prepared runway depends, among many other characteristics, upon the size of the runway. Current guidance indicates that the minimum size semi-prepared runway for C-17 operations is 4,100 feet long by 90 feet wide (AFCESA/CES, 97). This includes the 3,500 foot landing surface and two 300 foot overruns on each end of the runway. Given current procedures, a 4,100 foot runway would only be of use during dry runway conditions since planned stopping distance increases greatly under wet conditions when using an RCR of 4 as discussed previously. The Engineering Technical Letter, which provides guidance to civil engineers indicates that C-17s require a 7,000 foot runway during wet runway operations (AFCESA/CES, 1998). Obviously the requirement for an SBA could arise in any type of climate and weather and the ability to find 4,100 feet of useable surface is easier to find than 7,000 feet. Maintaining a 4,100 foot runway is also monumentally easier than maintaining a 7,000 foot runway. Further ***aircraft*** testing could possibly refine these calculations to something closer to the wet pavement RCR value. This could reduce the calculated landing distance from 5,370 feet to approximately 3,820 feet, a more manageable distance.

Analysis of Alternatives

In the eventuality that the C-17's semi-prepared runway capability cannot be developed to the level required, the JICT explored other options. While there are alternatives, most were ruled out after analysis showed they would extend the SBA timeline and or be unable to deliver the outsized equipment.

Increase the Size of the Airdrop Package

One option is to put part of the Bravo Echelon equipment into the Alpha portion and airdrop it. While this option would seemingly be able to meet the 24 hour closure time, it does raise some important issues. For force protection reasons, the XVIII Corps requires the Air Force to complete the airdrop of the Alpha Echelon within 30 minutes since it is believed that 30 minutes is the minimum time an enemy force would require to react to the airdrop and initiate a military response. Adding additional airdrop sorties would break the 30 minute barrier and unnecessarily expose aircrews and troops to added risk (McWhorter, 2002). In addition, airdropping more equipment onto the same drop zone increases the likelihood that equipment dropped later in the airdrop could land on and damage equipment dropped later in the airdrop. Finally, adding more airdrop sorties to the mix increases the logistical challenges since each additional airdrop aircraft translates into an additional requirement for more tankers and the requirement for more cargo to be loaded and prepared for airdrop under the same time restrictions. These issues combined with the possible requirement to increase the size of the drop zone to accommodate more equipment caused the JICT to rule out this option (Svisco, 1998).

Increase the Amount of Runway Repair Equipment and Personnel

Another option was to increase the amount of runway repair equipment and personnel delivered during the SBA. This option was deemed infeasible since there was still no guarantee that the engineers would be able to keep the airfield open throughout the airland portion. Additional engineers and equipment also means more sorties and longer drop times and was ruled out for the same reasons as the previously considered option of increasing the airdrop package (Svisco, 1998).

Use of Other Airlift Platforms

Since the C-141 and C-5 are not capable of landing on semi-prepared runways, they were ruled out as alternatives to the C-17 for the SBA Bravo Echelon insertion. This leaves the unrefuelable C-130 which requires an intermediate staging base (ISB) for objectives outside the range of the C-130 and cannot carry outsized cargo. The requirement for an ISB increases the time required for the entire SBA and results in additional access problems. When this increase in time was combined with the relatively slow speed of the C-130, it was deemed unlikely that the C-130 option could meet the required timeline. In addition, the JICT believed that a semi-prepared runway would have to be shut down for repair given the sheer number of C-130 sorties required to deliver the same amount of cargo as 48 C-17s regardless of whether C-17s were used only for the outsized cargo or not at all since 4-5 C-130 sorties are required for every C-17 sortie. Army officials believe that once there are enough C-17s, it is the only aircraft with the potential to deliver the entire SBA requirement within the necessary timeline to a paved surface (McChrystal, 2001). Therefore, it would be burdensome to have two plans, one for paved surfaces utilizing C-17s and one for semi-prepared runways utilizing C-130s. Since the C-130 appears unable to meet the timeline, and there did not appear to be any other advantages to using the C-130, this option was ruled out (Svisco, 1998).

Extending the Timeline for an SBA into a SPR

The final option explored by the JICT was to simply extend the timeline for bringing the SBA into a semi-prepared runway. While this option was deemed most palatable to members of the JICT and was viewed as the only viable option given current shortcomings, this extension was never formalized and the 48-hour target for full SBA insertion remains intact.

Summary

While other options to the C-17 do exist, these options have been ruled out for various reasons. Unlike the C-130, the C-17 can carry the outsized equipment, and with upgraded capabilities currently in the works it can meet the required 30 minute pass time requirement for the airdrop of the Alpha Echelon required by the Army. Combined with it's relatively high speed and unlimited range due to air refueling, the C-17 is the only platform from which the forcible entry capability can be launched within the time and distance requirements set by the DPG. While the SBA Joint Integrated Concept Team, (JICT) determined that the C-17 cannot currently meet the requirement to insert the SBA Bravo Echelon into a semi-prepared runway environment, it also determined that the C-17 is the only aircraft with the potential to fully meet the demanding SBA requirement. The JICT also determined that developing the C-17 semi-prepared runway capability is the best alternative. In summary, the C-17 offers the greatest potential for executing the full-range of SBA missions once this capability is refined.

V. Conclusions and Recommendations

Where is the prince who can afford so to cover his country with troops for its defense as that 10,000 men descending from the clouds might not in many places do an infinite deal of mischief before a force could be brought together to repel them

-- Benjamin Franklin

It is apparent that the C-17's semi-prepared runway capability requires development. This development should be comprehensive and should be given a high priority from both the Air Force and the Army. The development program should focus on resolving the following issues and *should include developmental evaluations in climate and soil-type combinations representative of those found in areas of potential operations throughout the world.*

High-Intensity C-17 Operations on the Semi-Prepared Runways

Since this is the largest issue facing the C-17, it requires the most attention. The focus of this development effort should be to keep landing C-17s on an unstabilized semi-prepared runway until either the rut depth, or lose till prevents further C-17 operations. At this point, the runway should be repaired and C-17 operations continued until the runway once again fails to the point where C-17s can no longer operate. This will provide airfield engineers some real data to be used in rut and loose till generation models and with expertise on how to best repair failed semi-prepared runways.

Procedures should be developed which limit the amount of damage intense braking action does to a semi-prepared runway. As an example, there are anti-skid braking systems currently available on the commercial market which allows pilots to select sensitivity based on mission needs (Aerospace, 2002). These anti-skid systems can be linked to automatic braking systems which could potentially reduce the runway deterioration which results from the maximum braking action. This may be possible since the computer controlling the braking constantly updates its position on the runway during the braking sequence and applies the appropriate amount of braking to ensure that the aircraft stops within the confines of the runway. By reducing the maximum level of braking and spreading the braking out over the entire length of the runway, this type of braking system could possibly equalize the damage over the entire length of the runway resulting in more passes prior to runway failure. These types of systems should be tested on C-17s to determine their ability to reduce runway deterioration. Additionally, tire research should produce a tire which can support slightly greater gross weights for semi-prepared runway operations allowing the C-17 to carry the M-1 and enough fuel to reach the nearest intermediate staging base without the requirement for immediate refueling.

An intense engineering research project should be undertaken to determine the runway repair method(s) which provide(s) the best combination of speed and durability following repair. In order to do this, a runway would have to be allowed to completely fail and be rebuilt as mentioned earlier in this chapter. If it is determined that certain soil types are just unable to support the weight of C-17s for more than a few landings, alternate concepts of operations should be developed. If, for example, it is determined that non-cohesive soil types found in arid climates cannot meet the requirements, then study should be made into using more than one, or two surfaces for delivering the SBA Bravo echelon. This would allow Runway X to undergo repairs while continuing operations on Runway Y. Or Runway X could be used for takeoffs only and Runway Y for landings only. This would allow the build up of loose till on Runway Y (the landing runway) to actually assist in the braking action as long as the depth of the loose till doesn't inhibit maneuvering. Since Runway X is only used for takeoffs, and takeoffs don't damage the surface as much, there would be less rutting and build up of loose till and aircraft could operate without fear of degraded takeoff performance due to loose till. When aircraft can no longer operate on the landing runway (Runway Y), landing and takeoff operations could continue on the takeoff runway (Runway X) until Runway Y is repaired when it could again resume operations as the takeoff runway. This scenario may require three landing/takeoff surfaces for uninterrupted operations. While the previous scenario is very rudimentary, it warrants further study. In many locations this concept of operations may not be possible, due to available real estate on which to lay out the two to three landing surfaces. In arid locations, however, such as the area in which Rhino LZ was located, there may be ample area clear of vegetation, etc, or which may be easily cleared which could be used as a runway surface. The need for such a concept of operations would also be greater in these climates due to the non-cohesive nature of the indigenous soils and the lack of available moisture.

A focus of the development of the C-17 semi-prepared runway capability should also be on emerging technologies. Some dust palliatives, in addition to controlling dust, have stabilizing effects, when used superficially and can increase the number of landings a semi-prepared runway can support. This is especially true in the case of polymer-based palliatives (Tingle, 2002). Engineers at the Waterways Experimental Station in Vicksburg, MS are studying different stabilizers in an effort to reduce the cure time of these substances, although there is no magic solution which can instantly harden an unstabilized surface.

Predicting the Performance of Semi-Prepared Runways

As mentioned previously, the ability to predict the number of landings possible on a surface without extensive on-site testing is a critical capability. The inability to accurately predict this critical limitation reduces the options available to commanders for implementing national policy.

This limitation exists for two primary reasons. First of all, there is relatively very little test data which can be used as a basis for modeling semi-prepared runway behavior. While Phase I SPRO testing did provide some data, the scope of this testing (10 landings on one semi-prepared runway) was woefully inadequate in comparison to the challenge of landing 48+ sorties on a semi-prepared runway without any maintenance. As a minimum, a flight test strategy should be developed to provide the data required for those soil types and climate based upon operational scenarios and the world-wide distribution of soil types and climates. This strategy would not be cost prohibitive and would greatly increase the reliability of unstabilized semi-prepared runway performance predictions.

The second reason for the inability to predict the number of landings prior to the need for maintenance is the current use of CBR as the sole measurement. As chronicled in the description of evaluations conducted at Rhine-Luzon LZ and Tyson LZ, CBR can be misleading. Therefore, a new measurement device must be developed which provides a more direct measurement of actual shear strength and one which can simulate the trauma associated with landing heavy aircraft on dirt, and therefore, predict the ability of the *in situ* soil to withstand the impact. This device must be portable and easy enough for advance teams to use in the field under the most rudimentary conditions. Such a device would require testing to validate the accuracy of the tool This testing could be a subset of the testing already advocated in earlier sections. The development of such a tool would allow engineers to refine models which could predict with a degree of accuracy the ability the life of a semi-prepared runway under almost any conditions.

The ability to predict the life-span of unstabilized semi-prepared runways may be the most important piece of the semi-prepared runway puzzle. Without this ability to reliably predict the life-span, the SBA mission will never be executed into a semi-prepared runway no matter how robust this capability may prove through further development. No commander would send this mission to a semi-prepared runway without knowing that the runway could, in fact, support the intended operation. Without reliable predictability, this deterrent loses part of its deterrent ability.

Takeoff and Landing Data (TOLD) Calculations.

The ability, or inability, to accurately account for the peculiarities associated with calculating takeoff and landing data especially on wet semi-prepared runways is another integral piece of the semi-prepared runway puzzle. Problems with VMCG, wet semi-prepared runway friction values, and RFF data must be refined. Failure to do so also weakens the deterrent capability of the SBA mission, especially in climates where wet conditions are likely. A portion of Operation ALLIED FORCE took place during the Balkan rainy season and the ability to operate into and out of semi-prepared runways would have been severely limited under wet conditions.

Future Semi-Prepared Runway Development Opportunities

Now that the Army has clearly defined the requirement that SBA include semi-prepared runway capability, the Army and Air Force must take advantage of every opportunity to make this concept a reality. The ultimate goal should be to demonstrate the ability to deploy the Bravo Echelon into a semi-prepared runway located in an arid/semi-arid climate since this is the worst case scenario. Until the capability can be demonstrated, the SBA's deterrent value is limited especially as it relates to possible objectives located in arid/semi-arid regions of the world with few concrete or paved runways.

PHASE II Semi-Prepared Runway Operations Testing

Phase II SPRO testing is the next round of SPRO testing designed to build upon the experience of Phase I SPRO testing. The four projects which make up PHASE II SPRO Testing will build upon experience gained and correct shortfalls identified during Phase I testing. Project 1, Lakebed Testing will measure the aircraft's response to rough runway conditions. Project 2, JA/ATT participation is a major portion of the testing program and will evaluate runway response to C-17 operations on semi-prepared runways which represent soil types/climate combinations similar to those found on 65% of the world's unforested surface (SPO, 2000). This project requires the use of four additional semi-prepared runways representative of the conditions being evaluated. Funding has been approved to accomplish this part of Phase II Testing through JA/ATT and exercise participation (AMC/XPR, 2002). Test planners will attempt to record the data from 160 landings on the four LZs to gather the requisite amount of data and gain more experience in semi-prepared runway behavior. The completion of Project 2 or Phase II SPRO testing will begin to provide the types of data needed by engineers to develop models which can more accurately predict the number of passes possible on a given semi-prepared runway. Project 3. Lab Projects, will continue research in soil stabilization with the goal of minimizing time to stabilize semi-prepared runways as well as control dust and FOD. The lab projects will also work toward refining TOLD calculations for semi-prepared runway operations and tools which can accurately measure the ability of a semi-prepared runway to withstand C-17 operations and therefore predict the number of passes possible prior to required maintenance. Project Four will evaluate wet vs. dry semi-prepared runway operations as well as operations in deep till with the goal of refining TOLD calculations for all conditions.

Additional Opportunities

While Phase II testing is an ambitious plan, it requires sponsorship at the highest levels of both the Army and Air Force. Both the Army and Air Force must also be willing to set aside assets to make this concept a reality and share the costs of this development. The development of this capability to the required level will not come cheaply. In addition to the costs involved in allowing runways to deteriorate and the costs of repairing those runways, there will be costs associated with the wear and tear on the airplanes used during the testing. There will be huge manpower costs for the engineers, aircrews, maintainers, and equipment operators, to name a few. Diverting aircraft away from paying customers carries with it the cost of lost revenues. The estimated costs of Phase II SPRO Testing alone is in excess of $15M to be shared in some way by the Army and Air Force (SPO, 2000).

The move from concept to reality will require an unprecedented level of commitment and cooperation from the Army and Air Force. In addition to planned test programs, the two services must be willing to land on dirt whenever possible and to have engineers on site who can gather the appropriate data for further analysis. All joint Army-Air Force training should be focused on SBA and semi-prepared runway operations. Prime examples of this joint training are JA/ATTs (Joint Airborne/Air Transportability Training), Large Package Week, exercises involving large formations planned about every eight weeks and Purple Dragon, a very large formation exercise which occurs every 18-24 months. Since a large number of landings on the same LZ is required, the Large Package Week and Purple Dragon provide outstanding opportunities to develop semi-prepared runway operations. While these occasions will provide excellent opportunities to refine and develop the semi-prepared runway capability, they also provide excellent opportunities to demonstrate the joint capabilities of the Army and Air Force in projecting forces anywhere in the world. These opportunities should be maximized and take on an elevated priority to ensure their completion.

Conclusion

While the C-17 cannot currently fulfill the Army requirement to deliver the SBA Bravo Echelon to a semi-prepared runway within the required time, this capability can possibly be developed without costly aircraft modifications or major procedural changes. The Army and Air Force must maintain an aggressive on-going development program designed to provide engineers with the ability to not only to design, build, and maintain semi-prepared runways, but also the ability to predict the number of passes an unfamiliar semi-prepared runway can support without repair. This on-going development program will also give aircrews the needed exposure to semi-prepared operations and will help correct current inaccuracies in TOLD calculations.

The C-17, due to it's outsized cargo carrying capacity, unlimited range due to air refueling, and short-field landing capability is the only aircraft in existence with the potential for accomplishing this mission without restrictions. The semi-prepared capability of the C-17 must be developed. While other options are available, they do not provide the flexibility, speed, and therefore, lethality that the C-17 delivers to the warfighter.

The current shortfall in the ability of the C-17 to deliver the Bravo Echelon to a semi-prepared runway weakens the deterrent value of the SBA capability. The resolution of the outstanding issues highlighted in this paper will have applications not only for the strategic brigade airdrop, but will provide the wartime commander with a multitude of scalable options and unrestricted access to any point on the globe.

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