EXPLOSIVE EVALUATION: GELLED NITROMETHANE AND SLURRY AS MILITARY BULK EXPLOSIVE SYSTEMS

by

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Washington, D. C. 20314
The Office, Chief of Engineers (OCE), is funding a research program to investigate the potential of commercial bulk explosives for use in the theater of operations. A possible end result is a bulk explosive system consisting of aluminized nitrate slurries, and mixing and pumping units similar to those used in commercial quarrying and open pit mining. Another bulk explosive was developed for the ESSEX program which was funded by Defense Nuclear Agency and OCE. This system uses nitromethane, a special gelling agent, and a mixing unit (Continued)
20. ABSTRACT (Continued).

to produce gelled nitromethane. This product has many characteristics that are similar to slurry blasting agents.

A slurry is a blasting agent which is a mixture of an oxidizer and a fuel or sensitizer in a liquid medium, thickened with a gum and gelled with a cross-linking agent for water resistance. The chemically active ingredients in most slurries are ammonium nitrate, water, and sometimes sodium nitrate or aluminum. Nitromethane is a nitroparaffin made by vapor phase reaction between nitric acid vapor and propane at high temperature and pressure. With a sufficient booster, it can be detonated; additives can make it cap-sensitive. Until recently, a satisfactory gelling agent had not been available for nitromethane. In recent tests, however, a modified guar gum has done an excellent job of gelling nitromethane. Both of these explosives are water resistant and will slump to fill the emplacement cavity. Of the two, nitromethane is more susceptible to charge deterioration under severe groundwater conditions. Gelled nitromethane performs much better at temperature extremes and has a much better shelf life than slurry, both as ingredients and in gelled form. Both explosives are safe to use, being noncap-sensitive and difficult to burn. However, nitromethane is more hazardous to work with than slurry because it may be pumped only within closely controlled pressures.

It is concluded that at present, an aluminized slurry system offers the best alternative for an Army bulk explosive system. Research has been extensive in the slurry industry and rapid advances have been made in the technology. High-energy slurry products are available which are excellent cratering explosives. The problems of slurry mentioned in this report have not been considered problems in industrial operations, and thus have not been adequately addressed. Gelled nitromethane could be considered as an alternative to a slurry system if the difficulties peculiar to slurries cannot be overcome.
THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.
The Office, Chief of Engineers, is funding a research program entitled Military Engineering Applications of Commercial Explosives (MEACE) to investigate the potential of commercial bulk explosives for use in the theater of operations. A possible end result is a bulk explosive system consisting of aluminized nitrate slurries, and mixing and pumping units similar to those used in commercial quarrying and open pit mining. The MEACE program is investigating these commercial bulk explosive systems.

Another bulk explosive was developed for the ESSEX program which was funded by Defense Nuclear Agency and the Office, Chief of Engineers. This system uses nitromethane, a special gelling agent, and a mixing unit to produce gelled nitromethane. This product has many characteristics that are similar to slurry blasting agents.

This study compared slurry and gelled nitromethane for potential application in military bulk explosive systems. It was conducted during the period from April 1973 through March 1974 by CPT H. H. Reed, CE, under the supervision of MAJ L. C. Webster, CE, Military Program Manager, and LTC R. R. Mills, Jr., CE, Director, of the Explosive Excavation Research Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES). The function of the Explosive Excavation Research Laboratory has now been reorganized within the Weapons Effects Laboratory at WES. CPT Reed is the author of this paper.

BG E. D. Peixotto, CE, and COL G. H. Hilt, CE, were Directors of WES during the conduct of the study and preparation of this report. Mr. F. R. Brown was Technical Director.
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U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

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</table>

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.
EXPLOSIVE EVALUATION: GELLED NITROMETHANE AND SLURRY
AS MILITARY BULK EXPLOSIVE SYSTEMS

PART I: INTRODUCTION

1. The comparison of gelled nitromethane (GNM) and slurry or water gel systems covers a broad spectrum. Various areas include physical and chemical properties, detonation characteristics, safety characteristics, suitability for military requirements both logistically and operationally, and required pumping and mixing systems. Slurries are already being evaluated as candidates for a military bulk explosive system. Commercially, they have been and continue to be developed and used for bulk consumption. As an explosive, nitromethane has seen limited use commercially. It has been used mainly in nuclear simulation experiments by government agencies.

Nitromethane

2. Nitromethane is one of the nitroparaffins made by the vapor phase reaction between nitric acid vapor and propane at elevated temperature and pressure. It is used primarily as an intermediate in organic synthesis of certain pharmaceuticals, dyes, insecticides, and textile chemicals.\(^1\) It can be made to detonate using a sufficient booster, or additives can be used to make it cap-sensitive. Commercially, it has been used in its sensitized form in underwater shaped charges and in oil well fracturing; unsensitized, it has been used in scientific cratering experiments and as a component in other explosives. Until recently, a satisfactory system for gelling of nitromethane had not been developed. Nitrocellulose has been used, but it is a high explosive in itself, and when mixed with nitromethane readily forms lumps which are difficult to disperse.\(^2\) This system was not considered practical or safe in terms of the quantities or conditions required for a military system.
Polyoxyethylene can be used to thicken nitromethane but a rigid gel is formed which will begin to liquefy after about a week of storage at room temperature. This gel can be further stabilized, but the rigid gel produced is not considered compatible with the need to mix, then pump or pour the gelled nitromethane into a subsurface cavity. Most starches, natural gums, and synthetic polymers used in water gelling systems are ineffective with nitromethane. General Mills, Inc., had been developing a modified guar gum, a cyanoethylether derivative of a galacto-mannan gum, specifically for thickening or gelling nitromethane. This gelling agent is identified as GenGel 512 by General Mills, Inc., and is a free-flowing white powder which must be quickly dispersed throughout the nitromethane to prevent the formation of lumps which are difficult to break up. This agent has done an excellent job of gelling nitromethane in large and small tests conducted as part of an explosive cratering test program. Cross-linkers are also available which work well with GenGel 512.

Slurry

3. Commercial operations requiring large amounts of explosive energy for earth moving tasks, such as open-pit mining, have come to depend on bulk loading explosives and blasting agents in order to hold down costs. (A blasting agent is a substance intended for blasting which cannot be detonated by a No. 8 commercial blasting cap and which is not otherwise classified as an explosive.) One of the most common types of blasting agents is that group of products called water gels or slurries.

4. A slurry is essentially a mixture of an oxidizer and a fuel or sensitizer in a liquid medium, thickened with a gum and gelled with a cross-linking agent. The earliest slurries used Government surplus TNT as a fuel-sensitizer but the majority of slurries used today do not contain high explosive ingredients. Great advances have been made in slurry formulations since they were first introduced. Many different ingredients have been used to produce a variety of slurry formulations.
with differing explosive properties.

5. The terms "slurry" and "water gel" are used interchangeably, though technically a water gel is usually considered a slurry which has been cross-linked to provide better water protection. The term slurry, however, is used more commonly. A slurry explosive either contains an ingredient that is classified as a high explosive or is sensitive to a No. 8 blasting cap. A slurry blasting agent does not meet either of these two criteria and is therefore under less restrictive storage and transportation regulations. The following description concerns only slurry blasting agents.

6. The chemically active ingredients in most slurry blasting agents are ammonium nitrate (AN), water, and sometimes sodium nitrate or aluminum. Typical slurries contain 40 to 75 percent ammonium nitrate, 15 to 25 percent water, 1 to 5 percent stabilizing and gelling agent, plus aluminum or another fuel or both. The addition of large quantities of aluminum produces an explosive with very high energy release at moderate detonation pressures. Energy release per unit weight can exceed twice that of ANFO, and these slurries can excavate up to 80 percent more volume per unit weight than ANFO or TNT. However, energy release per unit cost is about the same as non-aluminized slurries and approximately one-third that of ANFO.

7. Slurries are thickened and gelled with a gum, such as guar gum, to give them considerable water resistance. The gelling agent in slurries serves two purposes: (1) to insure a homogeneous mixture and prevent the settling of components, and (2) to facilitate handling. The slurry and gelling agent can be mixed while the explosive is being pumped into the emplacement cavity where the slurry cures to a rubbery or jelly-like solid. Excellent coupling with the surrounding medium is thus assured, and void spaces within the explosive are minimized. Most slurries are heavier than water (1.1 to 1.6 g/cm\(^3\)) and, being highly water-resistant, may be emplaced under water. The consistency of most slurries ranges from fluid near 38°C (100°F) to rigid at freezing temperatures, although even at freezing temperatures some slurries maintain fluidity.
8. Slurries require adequate priming with a high-velocity explosive to attain proper detonation velocities. They tend to have unconfined critical diameters of about three inches,* although slurries with unconfined critical diameters of less than one inch are available.

9. Ammonium nitrate slurries are frequently shipped and stored in plastic bags. For large operations where many thousands of pounds of slurry are used daily, sophisticated mixing and pumping units are available. These units allow loading of the slurry into boreholes at rates up to about 500 pounds per minute. They also allow the operator to vary the composition of the slurry as it is being pumped, enabling him to put a denser or more energetic mixture at the bottom of the borehole and a lighter, less energetic, and therefore less expensive product at the top of the hole.

10. For this report, the slurry selected for comparison with nitromethane is an aluminized blasting agent as this presently appears to be the most likely candidate for a bulk military system. Slurries have been investigated in some detail. Studies were done in early 1973 in answer to a series of questions from the Office, Chief of Engineers, and in early 1974 following a feasibility study done for Picatinny Arsenal by Hercules, Incorporated. Hercules studied the feasibility of a small mixing and pumping unit for military use and developed four candidate slurries.

11. Because slurries have been studied previously in some depth, this report will concentrate mainly on the properties of gelled nitromethane and not discuss slurries in great detail. Copies of two previous studies of slurries are included in Appendix A.

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.
PART II: DETONATION CHARACTERISTICS

Nitromethane

12. The explosive properties of nitromethane (CH$_3$NO$_2$) are listed in Table 1. Nitromethane is similar to TNT in detonation velocity and energy release but is a liquid and is much less dense. Its detonation pressure is high compared to slurries, but still is only about half that of TNT.

| Detonation Properties of Nitromethane$^2$ |
|-----------------|-----------------|
| Density         | 1130 kg/m$^3$   |
| Detonation Velocity | 6300 m/s       |
| Detonation Pressure    | 13.0 GPa       |
| Energy            | 1230 cal/g      |
| Volume of Gases   | 936 l/kg        |

13. Industrial grade nitromethane is relatively insensitive to shock compared with dynamos or military explosives. It cannot be detonated by a No. 8 blasting cap. It may be detonated if a booster of sufficient size is used. There are many ways in which pure nitromethane may be sensitized to make it cap-sensitive.$^3$ The use of organic amines as a sensitizer has been popular with commercial explosive firms. Other work is being conducted using mechanical sensitizers, such as micro-balloons, directed towards the use of nitromethane in explosive devices and systems for military applications.$^3$ The gelling process does not appear to change nitromethane's performance. The critical diameter, that charge diameter below which the material will not detonate reliably, is smaller for nitromethane than for almost all slurries. With an oxygen balance of -39.3 (TNT is -74.1), nitromethane does not have sufficient oxygen to completely oxidize all the fuel available.
14. Slurries are considered to undergo non-ideal detonation. This means that the explosive's detonation properties depend upon many parameters such as the charge size, degree of confinement, and type of priming. The critical diameter is generally several inches for bulk slurries. Most slurries require confinement and a high explosive booster to detonate efficiently. The pressure-time histories of slurries, which correlate with energy release, differ greatly from those of high explosives. Instead of exhibiting a very strong pressure which rapidly decays with time, as TNT or other high explosives do, metallized slurries have reduced detonation pressures followed by a sustained explosion pressure. This sustained pressure pulse results from the expanding gases produced by the relatively slow aluminum-oxidation reaction. This must be kept in mind when comparing explosives. Standard tests tend to overrate the high-detonation-pressure explosives. At present only the underwater energy test is able to provide an accurate evaluation of the total energy developed by slurries. Significant changes in the properties of slurries can be achieved by varying particle sizes of the oxidizer, particle size and surface coatings of the aluminum, and the amount and type of aerating agent used.4

15. Table 2 summarizes the specified explosive properties of the slurries developed by Hercules, Inc., under the Picatinny Contract.

| Table 2 |
|-----------------|------------------|
| **Explosive Properties of Slurries Developed** |                      |
| **by Hercules, Inc.** |                      |
| Density | 1200 to 1300 Kg/m³ |
| Detonation Velocity | 4000 to 4500 m/s |
| Energy | 1100 to 1900 cal/g |
| Percent Aluminum | 11 to 42 percent |
PART III: PHYSICAL AND CHEMICAL PROPERTIES

Nitromethane

16. In World War II nitromethane was tried as a propellant for rockets. Unfortunately, it would not burn reliably; however, it was discovered that moderate quantities of a few materials, particularly strong amines, would convert nitromethane into a cap-sensitive explosive. Spectacular accidents involving railroad tank cars of nitromethane in the late 1950s resulted in its being banned from shipping in anything greater than a 17E, 55-gallon drum. Thus, while nitromethane is still shipped as a solvent, it is recognized that under certain conditions of temperature, pressure, and confinement it can be made to mass-detonate.

17. The physical properties of nitromethane listed in Table 3 suggest qualities which make for easy handling. Its boiling point and vapor point are similar to those of water, but its freezing point is much lower. Nitromethane presents less fire hazard than do most organic solvents because of its relatively high ignition temperature and flash point, its low heat of combustion, its high density, and moderate solubility in water. It is less apt to become ignited, burns less vigorously, and its fires are more readily extinguished by water. As shown in Table 3, the flash point of nitromethane is 44.4°C; by contrast, the flash point of gasoline is about -43°C. Nitromethane is shipped and stored in 55-gallon ICC 17E drums with a capacity of 227 kg. The head space in each drum is filled with nitrogen. Nitromethane enjoys excellent storage life, especially if kept in its original container. In drums it is easily handled, shipped, and stored in large quantities.

18. Physically, nitromethane does have its drawbacks. It is a liquid solvent and as such is considered a moderate health hazard. The American Conference of Governmental Industrial Hygienists has recommended 100 parts per million as the threshold limit value for vapors in air for an 8-hour-per-day working exposure. If prolonged exposure to
<table>
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<tr>
<td>Vapor Pressure (at 20°C)</td>
<td>3.64 kPa</td>
</tr>
<tr>
<td>Freezing Point</td>
<td>-28.55°C</td>
</tr>
<tr>
<td>Density (at 20°C)</td>
<td>1138 kg/m³</td>
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<tr>
<td>Viscosity (at 20°C)</td>
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<tr>
<td>Heat of Vaporization (at b.p.)</td>
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<tr>
<td>Heat of Combustion</td>
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<td>Flash Point (tag open cup)</td>
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<td>Flash Point (tag closed cup)</td>
<td>35.6°C</td>
</tr>
<tr>
<td>Solubility in water (at 20°C)</td>
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</tr>
<tr>
<td>Solubility of water in NM (at 20°C)</td>
<td>1.75 percent wt</td>
</tr>
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</table>

the vapors is anticipated, a mask supplying fresh air should be used. A respirator with activated carbon should not be used in high nitromethane vapor concentrations. Skin exposure should not yield sufficient absorption to produce systemic injury, other than a slight drying effect because of a defatting action. It is considered only slightly toxic when taken internally.

19. Nitromethane is slightly acidic and corrosive. It is not recommended for storage in tanks of copper, brass, or other alloys containing copper. Lead or lead lined tanks must not be used. Nitromethane may affect other materials and all materials that would come in contact with nitromethane should be tested for compatibility. Nitromethane has the ability to partially dissolve most military high explosives and the booster should be protected.

20. A possible drawback of nitromethane is the ability of other materials to sensitize it which can result in increased susceptibility to both fire and explosion. The addition of caustic soda to nitromethane is hazardous and may result in a fire. Certain amines can make nitromethane a cap-sensitive explosive. Other chemicals can cause
reactions that produce explosive salts. Nitromethane can also be sensiti- 
zized slightly by the addition of small percentages of water and, as 
noted previously, it is soluble in water, thereby limiting its use 
underwater.

21. Nitromethane is sensitive to adiabatic compression; therefore, 
pumping pressures should not exceed 700 kPa (100 psi) and systems in 
which sudden stoppages might occur should be avoided. Any system should 
employ gravity flow wherever possible.

22. Although many gelling systems have been tried with nitro-
methane, the only effective agent at this time is General Mills GenGel 
512. This is a free-flowing powder which provides adequate gelling 
when used in percentages as low as 3 percent. It is non-explosive and 
needs only to be protected from moisture. Its shelf life, although 
untested, appears to be more than a year. This gelling agent requires 
a rapid mixing and dispersal before it has a chance to form lumps. At 
present, General Mills operates only a pilot plant to produce the 
guar gum. It takes a week to run one 90-kg (200-lb) batch and close 
quality control must be maintained.

23. The gelled product has been used at temperatures from -7°C 
to 32°C with no observed variations in its consistency. It has been 
noticed that on prolonged exposure to air the gelled nitromethane tends 
to evaporate leaving a crust-like film on the surface. The product was 
held at 38°C for several weeks with no appreciable gel breakdown noted. 
It has also been found that the gelled product can be appreciably con-
taminated with inert ingredients with only a slight decrease in the 
explosive's performance. Cross-linkers are available which can increase 
the gelled nitromethane's consistency and ability to protect itself 
against water.

24. Nitromethane in its original containers is very stable in 
storage and enjoys a long shelf life. It is unaffected by high tempera-
tures, but freezes at -28.5°C. There is no specific data on expansion 
during freezing, although field personnel who have worked with nitro-
methane in cold regions indicate that it does not expand and may actually 
shrink upon freezing. An organic antifreeze is available that can
lower the freezing point. In most cases, the thickened nitromethane solutions containing guar gum remain thick for at least one year. Sometimes there might be a slight gradual decrease in viscosity, but gels made with titanates as cross-linkers are very stable. General Mills believes the GenGel 512 is stable for at least two years and they are presently conducting storage tests. There is no biological breakdown in GenGel 512. 7

Slurries

25. A slurry is essentially a mixture of an oxidizer and a fuel or sensitizer in a liquid medium, thickened with a gum and gelled with a cross-linking agent. In general, the oxidizer-fuel reaction is primarily responsible for the energy produced by the explosion. The gelling agent serves to thicken the mixture to insure homogeneity, non-settling of components, and ease of handling. The cross-linker causes the slurry to set to a desired consistency and improves the explosive's protection against water. Water and various organic solvents are used to provide the liquid medium and improve the explosive's stability. Aerating and gas forming agents are used to increase the slurry's sensitivity. In less sensitive slurries, it is essential that micro-bubbles be available in the explosive to insure adequate detonation through hot spot initiation.

26. The physical consistency of slurries will allow them to be pumped directly from trucks or to be packaged in plastic bags. A slurry readily slumps to fill the borehole and the consistency also allows the slurry to be used underwater. Slurries are affected by hot and cold weather: in cold weather they may freeze, depending on how much anti-freeze has been added to the mixture; hot weather increases sensitivity and decreases storage life. 9 Most slurries do break down after prolonged storage and this is one of their drawbacks. Depending on storage conditions and temperature, breakdown can occur in as little as 6 months; warm weather tends to accelerate this process.

27. Slurries are difficult to classify chemically due to the
wide variety of ingredients that can be used to formulate them. Because reactive ingredients in slurries can cause dangerous reactions with some materials, routine compatibility checks are especially important. In slurries containing aluminum, the possibility exists for an aluminum-water reaction which releases hydrogen. Close quality control at the time of mixing is required to avoid this potential problem. If separate ingredients are stored and field mixed, then they may require special handling. This is especially true of ammonium nitrate and fine aluminum powders. Aluminum dust can become explosive. Ammonium nitrate can break down and become caked if subjected to moderate temperature cycling.
PART IV: SAFETY

Nitromethane

28. Unsensitized nitromethane is a relatively safe explosive. It is not cap-sensitive and has excellent safety characteristics as evidenced by its performance in standard safety tests. Differential thermal analysis tests show a large endotherm due to evaporating nitromethane and no exotherms are observed. Impact sensitivity of gelled nitromethane and a composition that had been contaminated with sand was determined using the LLL drop hammer test. Both failed to show reaction using a 2.5-kg weight at the limiting height of 1.77 m. A No. 8 blasting cap failed to detonate the gelled explosive. Gap tests were conducted on industrial nitromethane, a sensitized nitromethane, and a sand-contaminated gelled nitromethane. The gelled samples appeared to be only slightly more shock-sensitive than industrial nitromethane. A burn test was conducted by placing several pounds of the gelled explosive within a ring of combustible material and igniting the combustible material. The nitromethane did burn, but at a very slow rate with very little heat output and a very low, almost imperceptible, flame. Field tests conducted at Fork Peck again demonstrated the slow burning rate and low heat output of burning gelled nitromethane. A gel stability test consisted of keeping a sample in an oven set at 100°F for several weeks. No appreciable gel breakdown was noted.

29. The two main hazards associated with nitromethane are: (1) direct accidental initiation by the nearby explosion of a powerful explosive charge and (2) ignition and propellant burning of a large mass of confined liquid.

30. The Department of Transportation has banned the shipment of nitromethane in tank cars. There are no restrictions placed on nitromethane when shipped in ICC 17E, 55-gallon drums. In these drums, NM has been subjected to very drastic safety tests and has been found to be quite insensitive.

31. The Department of Defense has classified nitromethane as a
propellant. If it is contained in tanks or anything else other than an ICC 17E or C, 55-gallon drum it is considered to be in Propellant Hazard Group IV. The hazards from materials in this group are the same as for mass-detонating explosives (e.g., airblast overpressures and fragments from the containers and surrounding material).

32. Nitromethane is considered in Propellant Hazard Group II, which has much less stringent storage requirements if the following requirements are met:

a. Nitromethane is stored in unit quantities of 55 gallons or less in ICC 17E or C drums.

b. Drums are stored only one tier high.

c. Drums are protected from direct rays of sun.

d. Maximum storage life is two years unless storage life tests indicate product meets purchase specification at that time. Such tests are to be repeated at one-year intervals.12

33. Other safety considerations for nitromethane were covered in Part III: Physical and Chemical Properties. It can be sensitized, is compatible with some materials, is a mild health hazard, and is sensitive to sudden compression.

Slurries

34. Slurries are one of the safest explosives in use today. They generally pass all standard safety tests such as the cap test, impact test, bullet impact test, and friction test. Most slurries are extremely difficult to burn and if burning is successfully initiated, detonation rarely follows.9 While rough handling of any explosive is dangerous, slurries are the least likely to be affected by such handling. Various mixing and pumping methods have been used to handle slurry.

35. One area that needs investigation for any slurry used is the reaction that might occur with prolonged storage and gel breakdown. As pH control and ingredient suspension are important in proper slurry formulation, changes that might occur in storage must be checked for safety and performance reasons.
36. There are so many different formulations of slurries that no single safety classification can be applied. Depending on its specific ingredients, a slurry may be classified by the Department of Transportation as an oxidizer, a Class B explosive, or a Class A explosive. The Department of Defense has not classified slurries to date.
PART V: MIXING AND PUMPING UNITS

Background

37. In order to describe the advantages and disadvantages of slurry versus gelled nitromethane mixing and pumping operations, certain assumptions must be made concerning a gelled nitromethane system. This is necessary since the only nitromethane field mixing units ever tested were the DIAMOND ORE and ESSEX Units.\textsuperscript{10}

38. Commercial pumping and mixing operations may be grouped into two categories: a stationary plant mixing operation with pump-truck hauling to the site versus a mixing and pumping truck which does both operations on site. While both of these systems have been examined previously for slurries, it appears that the self-contained pumping and mixing truck is best suited for military operations. This conclusion, coupled with the fact that commercial nitromethane is not shipped or stored in bulk containers, dictates that only the portable pumping and mixing systems need be investigated and compared.

Nitromethane System

39. As mentioned previously, the only field tested pumping and mixing unit for large scale operations is the one used on ESSEX-I, Phase 1.\textsuperscript{10} This unit is shown in Figure 1. While this prototype unit is too bulky and inefficient for military use, it does illustrate the functions that must be accomplished. Conceptually, it should be possible to use either the batch mixing or continuous mixing systems common to slurry operations. Cross-linkers are available which could be added as the gel is being pumped downhole. The system would require low pressure equipment because pumping pressures should not exceed 700 kPa (100 psi). The system would also have to be carefully engineered to eliminate any areas where breakdowns or failures could result in a rapid compression of either the gel or the liquid nitromethane.
Advantages

40. The advantages of a nitromethane system are as follows:
   a. It uses a single component system requiring only the explosive, the gelling agent, and the cross-linker, if desired.
   b. No heat is required.
   c. Minimum mechanical operations and minimum separate auxiliary equipment are necessary.
   d. It is easy to operate as a small unit.
   e. Dirt contamination does not seriously affect explosive properties.
   f. Components are easily handled and have adequate shelf life.
   g. It has been field tested at -7°C to 32°C.
   h. The nitromethane system has low vulnerability in the drum form to detonation from an external charge or projectile.
   i. Nitromethane storage life could be indefinite. Nitromethane stored for approximately 6 to 8 years showed no chemical change that could affect explosive properties.
Disadvantages

41. The disadvantages of a nitromethane system are as follows:

   a. The explosive is less dense.
   
   b. Restriction on pumping pressures and sudden compressions may require more sophisticated equipment or limit loading speeds or capacities.
   
   c. A separate pumping unit may be required if adequate electrical shielding cannot be provided.
   
   d. Operation is more hazardous. It is a more hazardous liquid than slurry that can be sensitized by several types of materials.

Slurry Systems

42. Slurry pumping and mixing trucks have been developed commercially in various sizes, generally depending on the projected end use. Two types of operations are possible: either a batch or a continuous system. While the formulations of various slurries can alter the design of the system, the basic operations can be generalized. A truck or trucks must provide storage for the liquid medium, fuel, oxidizer, sensitizer, gelling agent, and cross-linker as required.

   43. The liquid medium is generally a solution of water, organic liquids, and dissolved oxidizer salts. The gelling agent may also be added to this as was done in the Hercules Military System. This is heated to keep the salts in solution and to insure rapid and adequate cross-linking. The fuel and sensitizer are introduced into the mixing container where everything is mixed and then pumped downhole. A typical commercial slurry mixing and pumping unit is shown in Figure 2. The cross-linker is generally added as the explosive is being pumped to avoid having the slurry set in the outlet hose.

Advantages

44. The advantages of a slurry system are as follows:

   a. Developed systems have proven effective in the field.
   
   b. Commercially developed, proven systems are available to meet a variety of requirements.
   
   c. Operations are inherently safer as slurries are
generally less sensitive than other explosives.

d. Ingredient feeds can be regulated to form a series of explosives of varying densities using the same basic ingredients.

e. The mixing and pumping unit requires no external power sources other than those with the truck.

f. Rapid hole loading is possible.

g. The slurry system can operate over a wide temperature range: $-20^\circ$C to $40^\circ$C.

**Disadvantages**

45. The disadvantages of a slurry system are as follows:

a. The commercial system requires heat for salt solution. This adds to equipment and power required, and personnel safety hazards.

b. To operate efficiently, the system is usually quite large.

c. The system is fairly complex requiring several feed pumps, a main pump, heating unit, and auxiliary power.

d. Each individual ingredient may require special handling and quality control.


46. Both systems have several common areas of concern. It is desirable to have a quick, safe system for transferring the explosive ingredients from storage to the Mixing and Pumping Unit (MPU). Both units require some power source. Both systems must be strictly safety-engineered. Despite what has been said concerning safety, the MPU is a small explosives manufacturing plant, an inherently dangerous operation. While these problems have been solved, they may be considered disadvantages in comparing either system to the present military explosives arsenal.
PART VI: OPERATIONS

Nitromethane

47. Unsensitized gelled nitromethane has many advantages as an explosive to include safety, effectiveness, and versatility. While nitromethane is an explosive similar to TNT, its increased gas production and lower detonation pressure make it more effective for cratering. Commercially, sensitized nitromethane has been used in shaped charges and oil well fracturing. It is possible to develop a variety of packages that could be filled and used for other tasks.

48. Nitromethane would probably be less effective as an external charge than the present military explosives, but probably more effective than slurry blasting agents. As a bulk cratering charge it has an attractive potential for use in the same type operations that are envisioned for a military slurry. As a fill for hardware items such as shaped charges and bangalore torpedos, it would have advantages because it will detonate in small diameters. A sensitization system such as microballoons might be required to make the gelled nitromethane cap-sensitive for some special-purpose fills.

49. Very little additional training would be necessary to teach demolition specialists how to properly prepare nitromethane for detonation. Training in handling the MPU would have to be more extensive, but not as extensive as would be required for the more complex slurry mixing and pumping truck.

Slurries

50. The OCE study (Appendix A) addressed primarily the area of operations. As envisioned in that study, slurries met an Army need for a bulk explosive system for use primarily in a cratering role in barrier and denial plans. Secondary uses were as external charges and in construction operations. Commercial applications of slurry are primarily in hard rock blasting. High-energy aluminized slurries have
proven effective in cratering work.

51. Training requirements would be similar to those required for nitromethane, though the MPU would be more difficult to operate. The slurry could be used anywhere in the battlefield due to its inherent safety and insensitivity.
PART VII: LOGISTICS

Nitromethane

52. As mentioned in Part IV, nitromethane has already been classified for Army use. Packaged in 55-gallon drums, it can be easily handled in transportation and storage. At this time only the 17E 55-gallon drum is approved for transportation. Normal care must be taken to insure drums are not punctured.

53. The pumping and mixing truck and the gelling agent would be two new items added to the inventory. A protected booster system would also have to be developed or a modified design adopted using items currently in the inventory.

54. At the present time nitromethane and other nitroparaffins are made commercially in two separate production plants operated by the Commercial Solvent Corporation in Louisiana. A new plant is being built in Bo'ness, Scotland, with production scheduled for July 1977.

55. General Mills presently makes GenGel 512 in a small pilot plant of limited capacity. They use the guar bean currently grown in Texas, India, and Pakistan as their basic material. Neither manufacturing process is extremely complicated and additional plants could be established if the requirement arose.

Slurries

56. Slurries would require new items be added to the supply system. Depending on the complexity of the slurry, more items would be required than for nitromethane. If a master mix system were used where an insensitive gel is used as one of the ingredients, then large quantities of gelled water and nitrates would have to be shipped, probably in 55-gallon drums. If separate dry ingredients were used, there would exist a heating requirement for the mixing and pumping unit. This requirement is based on the need to develop a supersaturated water-oxidizer solution as a part of the manufacturing process. With the
possible exception of a particular gelling agent, normal ingredients used in slurry formulation are available worldwide.
PART VIII: CONCLUSIONS

Detonation Characteristics

57. Gelled nitromethane is an adequate cratering explosive. Its higher detonation velocity and pressure would seem to make it a good explosive for use as an external charge. It will detonate reliably when contaminated by inert ingredients. A high-energy slurry is a better cratering explosive though probably not nearly as effective as an external charge. Both explosives require high explosives boosters and the booster used in nitromethane would probably require some sort of special protection from the nitromethane itself.

Physical and Chemical Properties

58. Both explosives are water resistant and will slump to fill the emplacement cavity. Of the two, nitromethane is more susceptible to charge deterioration under severe groundwater conditions. Gelled nitromethane performs much better at temperature extremes and has a much better shelf life than slurry, both as ingredients and in gelled form. Limited shelf life at present is a definite disadvantage of slurries.

59. While slurries do have some reaction problems, nitromethane is much more reactive chemically. It is a mild health hazard and can be sensitized by a number of materials as well as being incompatible with others.

Safety

60. Both explosives are quite safe to use, being non-cap-sensitive and difficult to burn. Nitromethane is more hazardous to handle and work with and it may be pumped only within closely controlled pressures.
Mixing and Pumping

61. Despite the restrictions on the pumping pressures of nitromethane, a mixing and pumping operation using it is a straightforward operation. Slurries, depending on the formulation, are much more complicated, requiring more rigid control and more equipment. Both operations require a simple, efficient material transfer system to increase operating efficiency in the field.

Operations

62. Both systems will require training of mixing and pumping operators. Slurries have demonstrated their earthmoving capabilities under a variety of conditions. Nitromethane, as a liquid, could cause some problems in the forward battlefield.

Logistics

63. Both systems add new requirements to the logistics system. The nitromethane requires fewer materials. Problems could arise due to the limited availability of nitromethane and gelling agents in the world. Additional plants might have to be set up. Slurries are used throughout the world and, while all ingredients for them may not be available worldwide, substitutes are usually available.

Overall

64. A gelled nitromethane system offers distinct advantages as a bulk explosive system for Army use. If the hazards associated with the liquid nitromethane are not considered severe with regard to troop handling and battlefield use, a definite study is warranted to evaluate nitromethane mixing and pumping systems. It would appear that such a program would have as a starting point the Project ESSEX work done by WES and LLL. No commercial companies have done much development
work in the area of nitromethane mixing and pumping systems.

65. At the present time it still appears that an aluminized slurry system offers the best alternative for an Army bulk explosive system. Research has been extensive in the slurry industry and rapid advances have been made in the technology. High-energy products are available which are excellent cratering explosives. The problems of slurry mentioned in this report have not been considered to be problems in industrial operations, and thus have not been adequately addressed. Certainly, if these problems cannot be overcome, then the gelled nitromethane system would seem an excellent alternative.
REFERENCES


7. Peter Calott, private communication, General Mills Chemicals, Inc., Minneapolis, Minn.


APPENDIX A

TWO STUDIES ON MILITARY USE OF COMMERCIAL SLURRIES

1. Appendix A contains two studies done by WES on the use of commercial explosives in the military and an evaluation of the feasibility study conducted by Hercules, Inc., for Picatinny Arsenal.
SUBJECT: Engineer Criteria for the Use Of Chemical Explosives (MEACE)

1. This letter is to reply to your letter of 26 September 1972 and to transmit a revised proposal for the study of military engineering applications of commercial explosives.

2. During the first half of FY 73 the Explosive Excavation Research Laboratory conducted a study to identify those military engineering applications for which commercial bulk explosives, in particular ammonium nitrate based aluminized slurries, offer a better alternative to current military explosives, and identify those areas for which further R&D effort is clearly indicated. Inclosure 1 answers each question posed in the inclosure to your letter. The answers to these questions and the results of the study can be summarized within four areas:

a. Operations. We feel that slurries can offer savings in time and manpower and can perform tasks not practicable with current military explosives, primarily due to their bulk handling characteristics. They offer a considerable improvement with respect to pre-emplacement, ease of neutralization, and ease of emplacement. The use of slurries would require training no more sophisticated than what is now required with current military explosives. However, a minimum one week training program would be required for the utilization and maintenance of a portable pumping and mixing unit for rapid explosive emplacement. The fact that slurries can be used in small quantities (tens of pounds) or in quantities equivalent to the yield of small ADM's (tens of tons) allows the combat engineer a wide range of applications, particularly in barrier operations and target destruction.

b. Logistics. A slurry system can be developed which will consist of inert, non-explosive ingredients mixable on-site to produce various explosive energies. The storage and transportation requirements for the slurry ingredients would be significantly less stringent than for explosives. On the other hand, slurries are designed primarily for
SUBJECT: Engineer Criteria for the Use of Chemical Explosives

use in large quantities and therefore they require certain pieces of specialized equipment for optimum use.

c. Environmental Constraints. Commercial slurries generally are not designed to meet the military standards for shelf life, ability to detonate under temperature and humidity extremes, and other environmental factors. However, slurries can be designed for longer shelf lives and for use under extreme conditions.

d. System Differences. The major differences between current military explosives and slurries are safety and bulk use. Slurries are less sensitive to detonation than military explosives. They can be shipped and stored as inert ingredients or in mixed form. In either case, they have less stringent shipping and storage requirements than military explosives. Since slurries are used in liquid or gel form, they are easy to use in very large quantities. Applications which are not practicable for current military explosives because of the handling associated with large quantities of small items become attractive with slurries because of their bulk handling characteristics.

3. As a result of this study a revised proposal for the study of Military Engineering Applications of Commercial Explosives (MEACE) has been prepared (Inclosure 2). The proposal calls for a coordinated effort over the next three fiscal years to address the following problem areas:

a. Selecting the best explosive(s) for the task.

b. Selecting the best equipment to emplace the explosive, and

c. Predicting the results of various emplacement designs.

Work under the MEACE program will be closely coordinated with elements of AMC, CDC, and USAES. Slurries will be field tested to develop design parameters and to demonstrate their feasibility for various military applications. State-of-the-art advancements in explosives technology and related equipment and novel drilling techniques will be monitored. The slurry mixing/pumping unit and the rapid ADM emplacement earth auger now being studied under ROC's developed by CDC will be field tested. Results of field tests, state-of-the-art summaries, and design data for field use will be published periodically in technical reports. To be completely successful, the MEACE program will require not only effort by WES elements, but also the accomplishment of certain tasks related to material testing and procurement by agencies not under WES or OCE control. Coordination with these agencies is essential. Estimated cost of the three year program is $1.5 million.

4. We feel that the MEACE program, in conjunction with the CDC and AMC development effort, will meet the objectives stated in paragraph 5 of your letter. First, a slurry explosive system, to include placement techniques and equipment, will be adopted to support military
WESEP
SUBJECT: Engineer Criteria for the Use of Chemical Explosives

12 March 1973

engineering in the field. Second, time- and manpower-saving techniques will be developed for the design and emplacement of slurries from small applications of deliberate road crater size up to large applications now allocated to ADM's. Third, technical information will be produced to aid in the development of doctrine and training for the introduction of a slurry system into the Army inventory.

5. In summary, I recommend the following actions:

   a. That the ROC for selecting slurries and a mixing-pumping unit be approved and evaluation studies be continued.

   b. That the ROC for selecting an earth auger for rapid ADM emplacement be approved.

   c. That OCE encourage continued AMC evaluation of novel drilling techniques.

   d. That the MEACE program be approved and funded at the levels indicated.

2 Incl
1. Answers to OCE questions
2. Proposal for the study of Military Applications of Commercial Explosives
Incl 2 wd

ERNEST D. PEIXOTTO
COL, CE
Director
SUBJECT: Questions and Answers to Suggested Questions by OCE on the Applicability of Slurry Explosives

1. Question: What is the anticipated distribution of Military Engineering Applications for explosives in a typical theater of operations?

Answer: An anticipated distribution of military engineering applications for explosives in a typical theater of operations has been split into the three general headings of target destruction, barriers, and military construction. Typically, the planned use of explosives has been primarily concerned with defensive operations in the areas of target destruction and barriers. This result is not surprising as the defense is characterized by attempting to channelize the enemy into established defensive positions and by denying or impeding the enemy's ability to advance. On the other hand, while explosives can play a significant role during offensive operations, their use can not be as vigorously developed as in the defense. In the support area also the use of explosives can not be rigorously planned. This is especially true with construction operations which depend in a large measure on what the particular area requires. With these limitations in mind, the following is a typical distribution of military engineering applications for explosives.

In a defensive posture, explosives play a primary role in establishing an effective barrier and denial plan. In the covering area where the halting and impeding of the enemy's advance is paramount, target destruction plays a primary role. The most likely targets are bridges, power lines, abatis, and tunnels. Obstacles in the form of cratering roads, airfields, and fords comprise the remainder of the applications in the covering area. In the forward battle area, the relative importance of these two applications would reverse. An extensive road crater and armor obstacle system might be used and only a limited number of targets in the form of bridges and abatis destroyed.
Data on the applications of explosives in the defense was obtained primarily from the ESSG study, "Demolition Target Evaluation."

During offensive operations, explosives often assist in maintaining the momentum of the attack by removing obstacles which impede the advance. Anticipated applications include destroying targets such as road obstacles, mine fields, protective structures, and wire obstacles. Forecasting for the moment, explosives could play a key role in helping to clear avenues through built up areas that have been subjected to nuclear attack.

In the support area, explosives are used almost exclusively as a construction tool. Lines of communication are maintained or constructed using explosively-produced rock or blast-produced road cuts. Bridges and other structures destroyed through previous combat operations are often removed explosively to make way for new construction. Craters may be created for POL storage or as protective areas. Water navigation may be improved explosively. Land clearing operations may require explosives. Target destruction and barrier applications are reduced primarily to the possibility of prepositioning explosives on bridges or in road crater chambers.

The specific applications mentioned above are by no means the only ones for explosives. Anyplace a tremendous amount of energy is required, explosives can be used. The limit exists only in the imagination and experience of the user. It must be recognized that many factors influence the distribution of these applications, not the least of which are the terrain and tactical situations. In this regard no attempt has been made to quantify these applications in the three areas discussed. It is felt that, generally, explosives are used much more in the defense than the offense, yet the amount of explosives used in several rock quarries in a theater of operations can far exceed that used in combat. Primary emphasis should be placed on the actions that occur in the forward area, but recent experience has demonstrated that modern warfare depends on what does or does not occur throughout the theater of operations.
2. **Question:** What explosives systems are presently being used for these applications?

**Answer:** The explosive systems that presently represent the military explosives arsenal are primarily based on high velocity plastic explosives such as C4 and PETN or RDX-based sheet explosives, TNT blocks, the ammonium nitrate catering canister, and military or commercial dynamites. These systems are designed to be fired either electrically or non-electrically using either detonating cord or firing wire to connect multi-charge systems. The high detonation velocity explosives such as C4 or TNT are considered as the primary charges for target destruction. These explosives, with their strong shattering action, are most effective as external charges in shattering or breaking steel, concrete or other strong materials. The primary military cratering explosive is the ammonium nitrate canister. Dynamites may also be used in this role though they are not recommended for use on the battlefield. Dynamites are generally considered for construction operations such as quarrying or road work. There are several other special military demolitions such as shaped charges or mine field clearing charges which have not been considered when addressing general engineering applications of explosives.

3. **Question:** What other explosives systems can be considered for these applications?

**Answer:** In considering other explosive systems for the military applications that are being addressed here, it must be remembered that theoretically any explosive should be capable of performing all types of military operations though practically, some applications would only be considered out of necessity. The areas of application mentioned below are considered the primary areas of impact.

Dry blasting agents, especially the 94 percent ammonium nitrate, 6 percent fuel oil known as ANFO, presently dominate the commercial explosives market. This explosive system has performed admirably in the mining and construction business. It fits admirably into the construction and cratering applications of military explosives. ANFO does have a major disadvantage in that it must be protected from
water. The military cratering canister serves that function for the dry blasting agent contained in it.

Slurry explosives are also primarily ammonium-nitrate based, but their formulations can be varied so that a wide range of explosives are available. These are also used primarily in the mining industry so they would best serve in the construction and cratering applications. Recent developments have led to cap-sensitive and small-diameter slurries which compare favorably with dynamites in effectiveness and are much safer. These slurries may also have some applications in the target destruction field.

Both dry blasting agents and slurries are free pouring and are readily applicable to bulk loading operations. Bulk loading cannot be applied to the present military explosives. This type of loading offers the promise of new techniques of explosive use in the areas of military applications where a quick, easily loaded, and gross system may be acceptable.

The liquid solvent nitromethane has been used as an explosive to some extent. While much more must be learned about the safety and handling aspects of this explosive before it could be accepted militarily, it does offer a potential as a liquid explosive that is comparable to TNT in properties.

Special purpose component-explosives are relatively new on the market. They are composed of two inert ingredients usually a solid and a liquid which are combined in the field to produce an explosive. This grouping does not include dry blasting agents or slurries. At present they appear to offer only limited application to military demolitions.

Fuel-air mixtures, while not technically classified as explosives, have been researched as to their applicability in mine-field breaching and soil-moving operations with some success.

4. Question: What are the international standardization considerations?

Answer: There are no international standardization considerations for the bulk ingredients of slurry explosives or the slurry. To
the best of our knowledge neither NATO nor STANAG have any provisions for the standardization of explosives except for quantity-distance separation tables. These tables do not apply to bulk ingredients, therefore, they would have to be adjusted if the ingredients were mixed and the resulting slurry was placed in storage. The U. S. quantity-distance separation tables for slurries are less restrictive than for other explosives.

5. Question: With regard to each application, what are the relative merits of the present and potential explosives systems with respect to the following?

Answer: With regard to each application, the relative merits of the present and potential explosives systems will be discussed in general at this point. Specific comments will be included in the remaining question areas where appropriate. In general, the military explosives family is composed of one component or ideal chemical compositions. This means that they perform very reliably and detonate with the same performance characteristics. The high velocity military explosives are most efficient in breaching steel and other hard structural materials. They are easily handled and detonated. They are not as effective as underground charges due to their high shock strengths. They are subject to stringent transportation and storage requirements. Military and commercial dynamites used by the military perform well in their construction roles but the nitroglycerin dynamites are considered the least safe explosives for the battlefield environment. Commercial dynamites require extreme care in the handling and storage and could present health problems if handled too long. The ammonium nitrate canister, while an excellent cratering explosive, must be protected from water and is restricted in its underground emplacement due to its rigid configuration. As mentioned previously, theoretically, all explosives are interchangeable in their roles, though most dynamites and ammonium nitrate make poor external charges. Generally, TNT may be considered as the general purpose military explosive although it too is limited in the field by its cast shape.

Dry blasting agents, especially ANFO, offer a definite safety
advantage due to its relative insensitivity. As an underground explosive it is free flowing, thus it fills any size emplacement hole and couples well with the surrounding medium. This coupling makes for most efficient blasts. As a bulk load, ANFO is rapidly emplaced and the ammonium nitrate and fuel oil may be mixed prior to emplacement. While ANFO performs more efficiently in larger boreholes, it can be detonated at diameters of 1/2 inch if loading conditions are favorable.

Slurries offer the same advantages as ANFO with regards to their safety, cratering, efficiency, handling, and coupling. As mentioned previously, a wide range of slurry products is available so that explosives may be formulated to perform certain demolition tasks. Slurries may be packaged in plastic bags or in bulk form. They may be site mixed thus presenting the possibility of mixing specific ingredients on site to perform a special military demolition application. A family of slurries could be developed that could meet all the application needs considered.

The specific limitations of the present military explosives are well known so that they will not be covered with regards to the specific questions about explosives covered below. All these comments apply to slurry explosives only since they are the most likely addition to the military explosives.

5a. Question: Suitability for a variety of explosives applications; i.e., cratering, demolitions and quarrying.

Answer: As mentioned previously, the present slurry explosives have been designed primarily for underground emplacement. In this configuration they have performed quite well, and thus they are suited for a variety of explosive applications in the construction and cratering areas. The ability to apply cratering techniques to target destruction applications is also available. This ability has not been exploited under the current doctrine. While slurries have not been tested as external charges for target destruction, they should be able to perform this mission if the need arose. For expedient target destruction where bulk explosives may be used, slurries may offer definite advantages, especially in time and manpower requirements.
5b. **Question:** Initial procurement considerations; i.e., costs, special materials, the R&D involved, specialized equipment, the ability to buy or otherwise obtain the explosive outside the U. S.

**Answer:** The initial procurement considerations vary widely for slurries due to the variety of ingredients that can be included in the formulation. The oxidizers required, such as ammonium or sodium nitrate, are readily available throughout the free world. Size gradations of the oxidizer might require some additional procurement expense but should not be difficult to obtain. The fluid medium consisting of water and other organic solvents is readily available. Aluminum in the grades and sizes required for specific formulations could be a problem in some areas of the world. Special procurement may be necessary to obtain the correct sized and surface treated aluminum. The research and development work in this area should be minimal as military specifications are already in use concerning aluminum grades. Certain varieties of gelling agents perform better. These may not be readily available worldwide. Since natural guars are subject to bacteria action, to improve a slurry's shelf life artificial guars are required. Explosive manufacturers have not addressed this problem to any extent as there is no overriding requirement to improve the shelf life of present commercial slurries. Synthetic guars may not be readily available worldwide. Commercial slurries are presently cost-competitive with commercial dynamites. The more rigid standards imposed by the military would result in increased costs. These costs would result from the additives and agents required to improve shelf life and other general chemical characteristics. They would probably not result in large R&D costs on the part of the Army.

5c. **Question:** Suitability for storage in Engineer Units versus Depot storage.

**Answer:** The question of storage suitability will be addressed in light of both packaged and bulk products. Bulk products probably offer the most advantageous situation since the relatively inert ingredients could be stored at both unit and depot levels. The main ingredients, ammonium nitrate and aluminum, must be protected from
direct sunlight and water. In addition, care must be taken in storing fine aluminum to avoid creating undue dust from the aluminum particles. As packaged products, the slurries could, again, be kept at unit or depot level. These would require explosive magazines (Type 4 or 5) and would have to be located in compliance with the American Table of Distances for Storage of Explosives when determining minimum distances to inhabited buildings, passenger railways, and public highways. Separation between magazines containing slurries is generally much less than that required for other military explosives depending, of course, on total weights stored.

5d. Question: Requirements for transportation precautions, such as special handling, procedures, and equipment.

Answer: Slurry explosives required no special handling, procedures or equipment. The Department of Transportation classification of Nitro-Carbo-Nitrate has been applied to dry blasting agents and slurries which contain no ingredients classified as high explosives or which are not cap-sensitive.

5e. Question: Requirements for emplacement to include time, personnel, and equipment.

Answer: The requirement for emplacement including time, personnel, and equipment is generally less than that required for present military explosive systems. The plastic bags may be slit and the slurry poured in the hole or they may be loaded directly in the bags. In boreholes this is usually much faster than either the canisters or dynamites. Dynamites usually take a longer time or more personnel as detonation cord must be laced through several sticks and then tamped into the hole. If a mixing truck is used, this naturally adds to the equipment required but holes may be loaded rapidly using a minimum of two people. As smaller external charges, the emplacement time and personnel would be about the same as for present explosives.

5f. Question: Suitability for preemplacement.

Answer: Slurries are particularly suited for preemplacement under almost all conditions. All slurries are quite water resistant and if left in plastic bags can be kept underwater for long periods of
time. The commercially available slurries today are formulated to perform best at ground temperatures generally encountered in boreholes. Instances of detonation of slurries after six months to one year underground have been recorded. As an external charge, the slurries could be preemplaced quite easily, but, unless the slurry has been formulated to withstand the external environment, it would probably be considered only marginally reliable after six months.

5g. Question: Ability to retrieve or neutralize.

Answer: The ability to retrieve or neutralize depends on how the slurries are being employed. As external charges, the booster would be removed making the slurry quite safe and the slurry could be returned to storage. Most slurries have critical diameters which are quite large compared to military explosives. The critical diameter is the diameter of charge below which detonation cannot be sustained. Thus, the slurry could be dumped on the ground and broken into small pieces by the action of water pressure. The small pieces would not be able to detonate. In boreholes, the slurry could again be rendered relatively safe by removing the booster. It could then be broken up by rodding and water pressure action. Some slurries could be neutralized by adding salt water or mild acid solutions.

5h. Question: Environmental constraints, such as humidity, moisture, and temperature.

Answer: The environment does affect slurry explosives. Before discussing these effects, however, it is appropriate to recall that the data collected to answer these questions is based upon the commercial slurries available today. These slurries are used in large quantities in mines and other blasting sites on a daily basis. There is no requirement to develop prolonged shelf life or high or low temperature performance in a slurry that is rapidly consumed in an environment such as rock where temperatures are fairly constant. Most explosive manufacturers quizzes felt that they could design slurries that could overcome the majority of these problems without an extensive research program being required.

The effect of environment on the shelf life of explosives
is related to the breaking down of the gelling agents after a period of approximately six months to a year. The primary reason for this is that bacteria attack and break down the natural guars used for gelling. Warmer temperatures increase the rate of this action, while colder temperatures retard it. This problem can be overcome by using synthetic guars or anti-bacterial agents. If the slurry ingredients are stored separately, both the ammonium nitrate and aluminum would have to be protected from water. The former to prevent caking and loss of sensitivity and the latter to prevent surface contamination. Some slurries gain their sensitivity by generating gas bubbles during formulation. These tiny bubbles act as hot spots or points of initiation. They tend to escape or join together during prolonged storage. This problem may be overcome through the use of mechanical microballoons in the slurry formulation.

The effect of the environment on the use of slurry explosives is mainly caused by temperatures. High temperatures make the slurry more sensitive by changing the quantity and size of the oxidizer in solution and in solid form. This can also affect the slurry's explosive properties. The solution for this has been to chemically cross-link the thickener to form a stable gel. Cold weather reduces the sensitivity of the slurry so that extra boosting might be necessary. The workability of slurry is reduced in cold weather. Most slurries are unaffected by water but high downhole pressures could reduce this protection.

5i. Question: Priming and booster requirements.
Answer: Slurries require a booster for initiation. Boosters are generally cast pentolite or composition B ranging in size from 1/3 to 5 lb with one pound being a common size. The boosters are initiated with either a blasting cap or detonation cord. A one-pound booster is generally sufficient to initiate detonation, though additional boosters may be placed along the charge length to insure detonation.

5j. Question: Chemical stability.
Answer: Chemical stability of slurry explosives has been greatly improved from early formulations. During temperature cycling,
the loss of small ammonium nitrate crystals through their going into solution and then recrystallizing as larger particles can affect the explosive properties though there has been no evidence that this affects the ability of the explosive to detonate. Some earlier explosives did produce gases at higher temperatures. This problem has been largely overcome. As outlined in section 5h, the stability of the gelling agents has the potential for having the most detrimental effects on the slurry.

5k. Question: Requirements for maintenance of the explosive and associated emplacement equipment.

Answer: There appears to be no foreseeable maintenance problems associated with present slurry explosives. The slurry mixing truck and pumping system would require that maintenance normal to like pieces of equipment currently in the Army's inventory.

5l. Question: Personnel training requirements.

Answer: The personnel training requirements involved in using a slurry explosive system would be no different than that required to train someone in normal military blasting systems. Someone trained in military demolitions would require a maximum of one hour training on a slurry system. If a slurry-mix is involved, discounting maintenance and driver training, at least a week would be required to learn the mixing and pumping operations.
MEMORANDUM FOR: Director

SUBJECT: Evaluation of Hercules Military Slurry System

1. Purpose. The purpose of this memorandum is to detail EERL's experiences with the four Hercules military slurries and to evaluate their potential as military bulk explosives.

2. Scope. This memorandum traces the history of EERL's association with the Hercules slurries, describes the field tests conducted using those slurries, and evaluates their potential in a military bulk explosive system. This memorandum is intended to provide information which may be used to support a Required Operational Capability (ROC) document for a military bulk explosive system. It is not intended to be a technical report on the field tests involved.

3. Background. In November 1972, the Engineer Agency (Mr. Abbott) of Combat Developments Command (now a part of the Engineer School under TRADOC) circulated a draft ROC on a Slurry Explosive System for comments from various agencies, including EERL, and for a cost assessment analysis by Picatinny Arsenal (Mr. Severini) of USAMC. Picatinny deferred comment until evaluation could be completed of a slurry system which was under study for them by Hercules, Inc. The Hercules study was based largely on the specifications in the draft ROC. The aim of the study was to select a family of slurry explosives which would vary in cratering performance from 1.5 to 2.5 relative to ANFO as 1.0. The study would also describe a mixing/pumping unit for use with the slurries. Hercules developed four specific formulas, representative of the "family" with total energies from 1.5 to 2.5 that of ANFO (based on underwater energy tests).

EERL was included in the distribution of the ROC and followed the Hercules work because of its Military Engineering Applications of Commercial Explosives (MEACE) Program, which is directed towards the adoption of a military bulk explosive system.

In February 1973, representatives of OCE, Picatinny Arsenal, the Engineer Agency, the Engineer School, and EERL visited the Hercules slurry operation at the Kaiser Eagle Mountain mine in Southern California. At this time, a mixing/pumping truck and the loading and storage equipment for a large commercial system were demonstrated.

In March 1973, at Picatinny's request, EERL proposed a
$50,000, two-part program to field test the four slurries Hercules had developed under their contract to Picatinny Arsenal. The proposal was approved and funded and two field tests were formulated. The first, for $15,000, was to be conducted in May 1973 in conjunction with National Guard maneuvers near Raystown, PA, and would compare the Hercules "C" slurry with standard 40-lb ammonium nitrate cratering charges in the production of deliberate road craters. The second, for $35,000, was to be conducted at Fort Polk, LA, in July 1973 and would compare the four Hercules slurries with ANFO, TNT, and two commercial slurries in a series of 500-lb cratering tests. Per agreement of the parties concerned at a meeting in Washington, D. C., on 11 September 1973, EERL would provide its evaluation of the Hercules slurries to Picatinny in early February 1974. Picatinny would provide its input to the ROC to the Engineer Agency by 1 March 1974, and the revised ROC would be forwarded for approval by 15 March 1974.

4. Description of the Hercules Military System. The Hercules military slurry system consists of a family of slurries, composed of a variable mix of four constituents, and of a field mixing/pumping unit. Four specific slurry mixes have been field and laboratory tested; the mixing/pumping unit is a paper conceptualization only, but does use simple, easily available mechanical components. Although the four-constituent scheme allows mixing of a wide range of slurry products, only four were actually mixed and tested.

The four constituents of the slurries are a master mix, an energizer, a sensitizer, and a cross-linker. The makeup of the master mix and of the four slurries is shown in Table A1.

Except for EGM, the slurry ingredients are relatively common throughout the industry. EGM is a product peculiar to Hercules slurries; other similar products are used by other explosives manufacturers.

Hercules proposed two mobile mixing/pumping units for use with its military slurries; a small batch unit capable of mixing one 5000-pound batch of slurry on a single loading and a larger continuous-flow unit capable of mixing 25,000 pounds of slurry on a single loading. Either unit could conceivably be hand loaded; however, some type of fixed-plant loading system would greatly increase efficiency. Only the small batch mixing/pumping unit comes close to meeting the ROC specifications in terms of total unit weight. No evaluation of either unit was made by this laboratory.

In order to mix a batch of slurry, the master mix must first be heated to at least 70°F to allow effective cross-linking to take place. Approximately 25 minutes would be required to heat the master mix to 70°F from 0°F in the small batch mixing/pumping unit. With either the batch or continuous-flow unit, the mixed slurry would be delivered (pumped) at a rate of about 500 lb/min.
SUBJECT: Evaluation of Hercules Military Slurry System

Table A1
Constituents of the Hercules Slurries

<table>
<thead>
<tr>
<th>Master Mix Ingredients</th>
<th>Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>22.14</td>
</tr>
<tr>
<td>Ammonium Nitrate</td>
<td>30.50</td>
</tr>
<tr>
<td>Calcium Nitrate</td>
<td>30.00</td>
</tr>
<tr>
<td>EGM (Ethylene-glycol-mononitrate)</td>
<td>12.00</td>
</tr>
<tr>
<td>Glycol</td>
<td>4.40</td>
</tr>
<tr>
<td>J251 (gelling agent)</td>
<td>0.36</td>
</tr>
<tr>
<td>Zinc Oxide</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>100.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Master Mix</td>
<td>84.81</td>
</tr>
<tr>
<td>Energizer (Aluminum)</td>
<td>11.00</td>
</tr>
<tr>
<td>Sensitizer</td>
<td>4.00</td>
</tr>
<tr>
<td>Microballoons (Chromic acetate)</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>100.00</td>
</tr>
</tbody>
</table>

The Hercules military slurries are classified by the Department of Transportation as Class B propellents. They are sensitive to a 1/4-lb cast primer at 0°F and to an Army cap (approximately equal to two No. 8 caps) at 120°F. The master mix is classified as an oxidizer, and it cannot be detonated by a 1-lb cast primer at 150°F in a 5-inch schedule 40 pipe. The volume energies of the four slurries are from 1.5 to 2.5 that of ANFO. They appear to have a minimum shelf life of 4 to 6 weeks; the master mix has a shelf life of about 16 weeks. The properties of the four slurries, as reported by Hercules, are shown in Table A2.

5. Field Tests.

a. Raystown. EERL's first use of the Hercules "C" slurry took place at Raystown, PA, in May 1973. Sixty-five hundred pounds were supplied as part of the Picatinny-Hercules contract. The test was designed to compare the effectiveness and the handling characteristics of the slurry with 40-lb AN canisters. Three deliberate road crater (DRC) test designs were fired with both the slurry and AN canisters; two other DRC designs were fired using the slurry only. Each design consisted of 3 or 5 holes, with 40, 80, or 120 lb of explosive per hole. The slurry charges were primed with 2-1/2-lb blocks of C-4. This primer
Table A2

Properties of Hercules Military Slurries

<table>
<thead>
<tr>
<th>Property</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/ft^3)</td>
<td>75.0</td>
<td>75.0</td>
<td>78.00</td>
<td>94.0</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.2</td>
<td>1.2</td>
<td>1.25</td>
<td>1.5</td>
</tr>
<tr>
<td>Energy (relative to ANFO)</td>
<td>1.5</td>
<td>1.8</td>
<td>2.10</td>
<td>2.5</td>
</tr>
<tr>
<td>Bubble energy (percent)</td>
<td>55.0</td>
<td>55.0</td>
<td>56.00</td>
<td>61.0</td>
</tr>
<tr>
<td>Shock energy (percent)</td>
<td>45.0</td>
<td>45.0</td>
<td>44.00</td>
<td>39.0</td>
</tr>
<tr>
<td>Detonation rate (m/sec in 4&quot; diam)</td>
<td>4500.0</td>
<td>4300.0</td>
<td>4150.00</td>
<td>4000.0</td>
</tr>
<tr>
<td>Stability at 120°F (weeks)</td>
<td>6.0</td>
<td>5.0</td>
<td>5.00</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Size was chosen because C-4 comes in 2-1/2-lb blocks and not because it was the minimum primer size required.

Table A3 is a partial listing of the crater dimensions of the Raystown tests. Because of varying site conditions, the results of the several shots were somewhat difficult to analyze. In general, however, it can be said that the slurry performed at least as well as the AN canisters with respect to crater dimensions. The important difference was that the fluid nature of the slurry allowed better coupling between the explosive and the soil. This implies--although it was not specifically tested—that less slurry could be used to achieve the same results as with the fixed size and weight AN canisters.

All of the slurry received at Raystown was used within two months of its manufacture. The gel appeared to be consistent and homogeneous but was somewhat sticky. No evidence of gassing or drying-out of the slurry was noted. There was evidence of slurry burning in the air on several of the detonations. This indicates that either the slurry was not buried deeply enough to fully confine the explosion and use all of the energy available or that there was insufficient oxygen available in the slurry to complete the aluminum-oxygen reactions below the ground and the reactions were completed in the air. Since the charge weight and depth of burial were fixed in these tests, the implication of the above-ground burning is that either less slurry could have been used to do the job or that the slurry mixture is fuel-rich and therefore uneconomical. There were no problems encountered with handling the slurry and it performed well in water-filled holes.

b. Project POKEHOLES. The second major test program involving the Hercules slurries took place at Fort Polk, LA, in the summer and fall of 1973. Three 500-lb shots of each of 8 explosives (ANFO, TNT, two commercial slurries and four Hercules slurries) were scheduled.
WESEP 74-20  
SUBJECT: Evaluation of Hercules Military Slurry System

Table A3
Partial List of Crater Dimensions DRC Experiments
Raystown, PA

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Crater Dimensions (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth</td>
</tr>
<tr>
<td>Test Design 1:</td>
<td>5</td>
</tr>
<tr>
<td>AN Canisters</td>
<td>7.6-10.1</td>
</tr>
<tr>
<td>Slurry C</td>
<td>8.3-9.5</td>
</tr>
<tr>
<td>Test Design 2:</td>
<td>3</td>
</tr>
<tr>
<td>AN Canisters</td>
<td>5-8</td>
</tr>
<tr>
<td>Slurry C</td>
<td>6-9</td>
</tr>
<tr>
<td>Test Design 3:</td>
<td>3</td>
</tr>
<tr>
<td>AN Canisters</td>
<td>8-12</td>
</tr>
<tr>
<td>Slurry C</td>
<td>10-15</td>
</tr>
<tr>
<td>Slurry C (Inclined holes)</td>
<td>10-12</td>
</tr>
</tbody>
</table>

to be fired in order to obtain a comparison of the cratering effectiveness of the several explosives. Each explosive was to be buried at a depth computed by empirical formulas to be optimum for cratering. Each charge was boosted with three 1-lb cast pentolite boosters in a cluster at the top third point. Diameter of all emplacement holes was approximately 15 inches. The two commercial slurries were selected as representative of high energy aluminized products and also to compare closely with two of the Hercules slurries. General information on the explosives used in Project POKEHOLES is contained in Table A4.

Crater dimensions for the POKEHOLES shots are shown in Table A5. Figure A1 is a plot of apparent crater volume versus energy density. The plotted line is merely a linear least squares fit to the data; it does not imply that crater volume can be predicted using that line or that explosive energy density is necessarily the best indicator of cratering effectiveness. Figure A1 does show, however, an expected trend of increasing crater volume with increasing energy. The same trend was generally true for other crater dimensions. Only the D slurry appears to have yielded craters smaller than expected. It should be noted that this is raw data; no account has been taken of anomalies in crater shape due to differences in the local water table. A near-surface water table, such as is the case at Fort Polk, appears to have
Table A4

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Density (Mg/m³)</th>
<th>Detonation Velocity (m/s)</th>
<th>Energy (MJ/kg)</th>
<th>Percent Aluminum</th>
<th>Price ($/lb)</th>
<th>Calculated DOBopt (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hercules A</td>
<td>1.2</td>
<td>4500</td>
<td>4.92</td>
<td>11</td>
<td>0.41</td>
<td>11.6</td>
</tr>
<tr>
<td>Hercules B</td>
<td>1.2</td>
<td>4300</td>
<td>5.91</td>
<td>23</td>
<td>0.41</td>
<td>12.3</td>
</tr>
<tr>
<td>Hercules C</td>
<td>1.25</td>
<td>4150</td>
<td>6.90</td>
<td>28</td>
<td>0.41</td>
<td>13.0</td>
</tr>
<tr>
<td>Hercules D</td>
<td>1.3</td>
<td>4000</td>
<td>8.21</td>
<td>42</td>
<td>0.41</td>
<td>13.7</td>
</tr>
<tr>
<td>Dow MS 80-25</td>
<td>1.2</td>
<td>4100</td>
<td>6.07</td>
<td>25</td>
<td>0.27</td>
<td>12.4</td>
</tr>
<tr>
<td>Ireco DBA 22M</td>
<td>1.43</td>
<td>4120</td>
<td>7.95</td>
<td>30</td>
<td>0.56</td>
<td>13.7</td>
</tr>
<tr>
<td>TNT</td>
<td>1.22</td>
<td>6930</td>
<td>4.60</td>
<td>n/a</td>
<td>2.40</td>
<td>11.3</td>
</tr>
<tr>
<td>ANFO</td>
<td>0.85</td>
<td>4560</td>
<td>3.28</td>
<td>n/a</td>
<td>0.14</td>
<td>10.1</td>
</tr>
</tbody>
</table>

profound effect on crater formation; i.e., when the charge is buried below the water table it causes wide, shallow, flat-bottomed craters as opposed to the classical crater shape. This is illustrated by the difference in two of the Hercules C slurry craters depicted in Figure A2.

During the POKEHOLES tests, a fire occurred which destroyed most of the initial shipment of Hercules slurry. Five days after arrival of the Hercules slurries, the bunker in the Ammunition Supply Point in which they were stored caught fire and burned. The bunker contained 4775 lb of Hercules slurry, 1650 lb of Herco Blasting Agent No. 1 (mistakenly shipped as a substitute for ANFO), 141 lb of pentolite boosters, and some 2.4 million rounds of small arms ammunition. An investigation into the probable cause of the fire was conducted by a Board of Officers at Fort Polk. The Director of the Waterways Experiment Station appointed an officer to conduct a technical investigation into the fire, and EERL coordinated a series of laboratory tests of materials involved which were performed by Picatinny Arsenal, Lawrence Livermore Laboratory, and Hercules, Inc. The tests included chemical analysis, thermal gravimetric analysis, differential thermal analysis, spectroscopy of gases emitted, and vacuum stability analysis of samples of the same lots of Hercules slurry and Herco Blasting Agent involved in the fire. Tests were also performed on the aluminum powder used in the Hercules slurries. Test results were provided to Picatinny Arsenal and to the Board of Officers.

None of the tests gave any clear indication of what might have caused the fire. Only two discrepancies were found during laboratory testing of the materials involved. It was noted that the Hercules C and D slurries exhibited an unusually low pH. This condition allows accelerated reaction of aluminum and water, with accompanying liberation
<table>
<thead>
<tr>
<th>Explosive</th>
<th>Shot No.</th>
<th>Date</th>
<th>DOB ft</th>
<th>L/D</th>
<th>R a, ft</th>
<th>R a, ft</th>
<th>D a, ft</th>
<th>D a, ft</th>
<th>V a, cu yd</th>
<th>V a, cu yd</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hercules A</td>
<td>1-2</td>
<td>3 Jul</td>
<td>11.3</td>
<td>4.8</td>
<td>21.6</td>
<td>25.2</td>
<td>6.8</td>
<td>9.8</td>
<td>253</td>
<td>396</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>2-4</td>
<td>18 Oct</td>
<td>11.3</td>
<td>4.5</td>
<td>19.8</td>
<td>23.0</td>
<td>5.6</td>
<td>8.3</td>
<td>164</td>
<td>256</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>3-3</td>
<td>6 Oct</td>
<td>11.6</td>
<td>4.2</td>
<td>19.5</td>
<td>21.3</td>
<td>8.1</td>
<td>11.0</td>
<td>153</td>
<td>279</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-4</td>
<td>17 Oct</td>
<td>11.2</td>
<td>5.1</td>
<td>19.5</td>
<td>22.2</td>
<td>10.2</td>
<td>12.7</td>
<td>190</td>
<td>303</td>
<td></td>
</tr>
<tr>
<td>Hercules B</td>
<td>2-5</td>
<td>3 Jul</td>
<td>12.9</td>
<td>3.4</td>
<td>21.8</td>
<td>26.2</td>
<td>10.0</td>
<td>13.0</td>
<td>235</td>
<td>406</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>3-1</td>
<td>18 Oct</td>
<td>12.1</td>
<td>4.7</td>
<td>26.6</td>
<td>31.8</td>
<td>9.6</td>
<td>13.0</td>
<td>468</td>
<td>752</td>
<td>Charge buried 1 ft deeper than planned</td>
</tr>
<tr>
<td></td>
<td>4-4</td>
<td>17 Oct</td>
<td>12.5</td>
<td>4.2</td>
<td>21.8</td>
<td>27.5</td>
<td>11.6</td>
<td>14.3</td>
<td>240</td>
<td>407</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>6-4</td>
<td>18 Oct</td>
<td>13.7</td>
<td>3.7</td>
<td>23.3</td>
<td>30.0</td>
<td>7.4</td>
<td>10.6</td>
<td>227</td>
<td>451</td>
<td></td>
</tr>
<tr>
<td>Hercules C</td>
<td>1-3</td>
<td>6 Oct</td>
<td>12.8</td>
<td>4.2</td>
<td>25.3</td>
<td>28.7</td>
<td>7.8</td>
<td>10.3</td>
<td>404</td>
<td>597</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>3-2</td>
<td>5 Oct</td>
<td>13.2</td>
<td>3.8</td>
<td>26.3</td>
<td>29.0</td>
<td>7.7</td>
<td>11.6</td>
<td>396</td>
<td>681</td>
<td>Shallow, flat bottomed crater</td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>5 Oct</td>
<td>11.3</td>
<td>6.9</td>
<td>18.0</td>
<td>21.3</td>
<td>9.3</td>
<td>11.6</td>
<td>120</td>
<td>207</td>
<td>Partial detonation, about 150 lb</td>
</tr>
<tr>
<td></td>
<td>6-2</td>
<td>3 Jul</td>
<td>12.8</td>
<td>4.8</td>
<td>22.7</td>
<td>28.8</td>
<td>15.1</td>
<td>17.8</td>
<td>308</td>
<td>518</td>
<td></td>
</tr>
<tr>
<td>Hercules D</td>
<td>2-2</td>
<td>17 Oct</td>
<td>13.6</td>
<td>4.5</td>
<td>25.8</td>
<td>29.7</td>
<td>8.7</td>
<td>11.3</td>
<td>395</td>
<td>581</td>
<td>Malfunction first try, about 650 lb detonated second try</td>
</tr>
<tr>
<td></td>
<td>4-1</td>
<td>4 Oct</td>
<td>13.7</td>
<td>3.7</td>
<td>22.8</td>
<td>26.7</td>
<td>14.5</td>
<td>17.1</td>
<td>303</td>
<td>448</td>
<td></td>
</tr>
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Figure A1. Average volume of craters versus energy density, Project POKEHOLES
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31 January 1974
SUBJECT: Evaluation of Hercules Military Slurry System

POKEHOLES EVENT 1-3, HERCULES SLURRY C.

No evidence of Water Table above el. 385

Center of charge

Figure A2. Average crater profiles, Project POKEHOLES Events 1-3 and 6-2
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of hydrogen gas and heat. No satisfactory explanation of the low pH could be given by Hercules. During the chemical analyses, there was no success in determining the EGM content of the same lot of Hercules slurries C and D involved in the fire. The significance of this problem was not explained. One other fact bearing on the investigation was that during development of the slurries, Hercules noted problems in stability of the slurries at elevated temperatures (120°F), especially with the high aluminum content slurries. No conclusive evidence was discovered to indicate the cause of the fire. However, the above-noted discrepancies and the relative novelty and complexity of the Hercules slurries have generated suspicion of them as a possible cause of the fire.

During loading of the first three holes (before the ASP fire), it was noted that there was gassing in slurries B and C sufficient to swell the plastic bags in which they were packed. This phenomenon was not seen with the second batch of slurries. One of the D slurry shots failed to detonate even though the booster detonated. The shot was re-primed and 150 lb more slurry added, and a successful detonation achieved. No apparent explanation for the malfunction was found. No other malfunctions of this type were encountered. No problems in handling the slurries were noted, although the second batch of Hercules slurries were not as solidly gelled and were much stickier than the batch which had been received in June. As in the Raystown tests, there were several shots where evidence of slurry burning in the air was noticed.

c. Demolitions Tests. A series of tests were conducted between 1 November and 3 December 1973 at the Waterways Experiment Station, Vicksburg, Mississippi, to determine the level of effectiveness of one of the Hercules slurries applied as a demolition charge.

Slurry A was selected as the demolition charge because it has the highest detonation velocity (4500 m/sec). A total of 36 tests was conducted, i.e., 11 steel plates having thickness of 1/4, 3/8, 1/2, and 1 inch, 15 wide flange steel beams, 5 concrete piers (12- by 12-inch cross section), and 5 timber piers (12- by 12-inch cross section). The age of slurry A at initiation of the testing was 39 days.

Bulk explosives, such as the Hercules slurries, were not designed for use as small external charges. Because of their wider detonation or reaction zones and lower peak pressures, they cannot compete on a small scale with standard military demolitions. There may be occasions to use them as expedient external charges and the purpose of these tests was to begin to develop the data base for such use. The tests did demonstrate that the A slurry can be used to sever structural members made of steel, concrete, or timber. Much more testing will be required before optimum placement of slurry charges can be realized.

During the test series, one bag of slurry was encountered that failed to detonate completely when initiated. This bag of slurry was
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used on 12 November 1973 and had been packaged 24 September 1973. The slurry appeared to be more watery than normal and had white streaks and small black specks throughout the mix.

d. Shelf Life. No formal testing of the shelf life of the Hercules slurries was made. However, several hundred pounds of the batches mixed on 24 September 1973 have been stored at the WES Big Black Test Site since 27 September and periodic observations of the slurries have been made.

The pH of slurries is an indication of their quality. The Hercules slurries are made at a pH of about 5.0. A rise in pH indicates that an aluminum-water reaction is taking place and the slurry is breaking down.

Observations of the Hercules slurries showed that on 27 September the pH's of the slurries were: A - 5.5, B - 5.5, C - 5.0, and D - 5.0. On 29 January 1974 the pH's were: A - 7.0, B - 6.2, C - 6.8, D - 6.8. On both occasions the slurries appeared to be in good condition with no visible evidence of breakdown.

6. Evaluation. This paragraph reflects EERL's appraisal of the Hercules military slurries and is based on our analysis of information provided by Hercules, performance of the slurries in field tests, and our knowledge of the state-of-the-art of slurry explosives. No evaluation of the engineering or potential performance of the mixing/pumping units proposed by Hercules is included.

a. With respect to the Hercules military slurries themselves, it is felt that the four-constituent concept is a good one, the minimum 70°F temperature requirement for mixing is not too severe, and that the slurry formulas are up-to-date with respect to the state-of-the-art. There are, however, certain drawbacks to the slurries and improvements are needed to qualify them as acceptable military bulk explosives.

(1) Shelf life of the Hercules military slurries is too short, i.e., 4-6 weeks at 120°F. This problem is due to the eventual reaction of the aluminum and water and to the breakdown of the gel structure. Both processes are accelerated at high temperatures. The shelf-life problem is not unique to the Hercules military slurries but is characteristic of aluminized slurries in general. However, commercial slurry products with considerably longer shelf lives are available. Minimum desired shelf life for a military slurry, in our opinion, should be about 3-4 months.

(2) Energy requirements of the Picatinny contract may have contributed to the shelf life problem. High levels of aluminum were added in order to meet energy specifications. In order to then meet sensitivity specifications more water and microballoons were added. The changes appear to have resulted in oxygen-poor mixtures for the C and D, and possibly the B, Hercules slurries, as well as producing the
short shelf lives. An oxygen-poor slurry does not do all its work in the ground where maximum energy release is desired; instead part of the aluminum reacts in the air, contributing little to crater formation.

(3) With respect to the master mix, the shelf life is too short (16 weeks) and the need to ship a solution containing 22 percent water is undesirable. The shelf life problem is caused by precipitation of the nitrate salts. Both drawbacks could be avoided by field mixing of the slurries from scratch. However, this would necessitate heating the ingredients to 150-180°F and would mean shipping and mixing an excessive number of ingredients. Neither situation would be desirable but may be necessary to allow a long (i.e., 5 years desired) shelf life.

(4) During field tests, nonuniformity in consistency of the Hercules slurries was noted; i.e., one batch was very stiff and well mixed; another was more jello-like in consistency and had definite flakes of material interspersed. Whether this was due to poor quality control in mixing or to some characteristic of the formulas is not known. Reproducibility of the slurry mix from batch to batch is necessary for a military explosive.

b. With respect to performance, the Hercules military slurries demonstrated effectiveness in both cratering and target destruction roles.

(1) The B and C slurries performed well as cratering explosives. The A slurry was adequate but did not perform proportionately as well as B or C; i.e., one can get the same results as for A by using less B or C with minimum increase in cost of explosive ingredients. The D slurry did not perform well enough to justify its high aluminum content and hence higher cost. However, more testing is required because it is possible that the D slurry shots were not buried deeply enough to take full advantage of its reported higher energy.

(2) All the slurries appeared to perform well in a wet environment and to be easy to handle.

(3) In preliminary tests, the A slurry has demonstrated that it can be used as an expedient for target destruction. However, more testing will be required before a definitive statement as to the worth of slurries in general in a target destruction role can be made.

c. Although nothing definite was proven in the investigation of the Fort Polk ASP fire, certain doubts about the safety and stability of the Hercules slurries were raised. Very careful investigation of the response of the slurries to various environmental conditions will be necessary if further work with these products is contemplated.

7. Conclusions.

a. Insofar as performance is concerned, Hercules military slurries B and C are acceptable candidates for military bulk explosives.
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b. The Hercules military slurries and their master mix have unacceptably short shelf lives. There is also doubt about their safety.

c. The requirements for a military bulk explosive system as stated in the PROC should be reevaluated. For example, the need for a "family" of products, as opposed to a single "all-purpose" explosive, and the need for very high-energy products should be reevaluated. The candidates should not be limited to slurries.

d. It appears that no "off-the-shelf" product will meet all the desired requirements of a military bulk explosive system (as defined by EERL). Research to achieve an acceptable military bulk explosive system should be vigorously conducted.

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MEACE Technical Deputy

CF:
DAEN-MER-D (LTC Hughes)
ATSE-CTD-MX (Mr. Abbott)
WESNV (MAJ Stroud)
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