DESIGN AND MUSKEG OPERATION OF THE 20 TON PAYLOAD CARRIER, THE MUSK-OX

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In a band girdling the top of the world, roughly from the latitude of the Twin Cities up to the Arctic Circle, much of the land is terrain generally characterized as "muskeg," which is singularly unfriendly to overload vehicles. Some 20% of northern Canada and the USSR is muskeg. Except during the months when it is frozen, there have in the past been but two ways to move tonnage in the more intransigent muskeg areas: build roads through it, or fly over it.

Unfortunately, much of the free world's mineral wealth appears to be secreted in the depths of muskeg country. It has accordingly become desirable to develop a third concept for dealing with transportation in such country: by means of vehicles capable of carrying cargo over the muskeg without benefit of roads.

This paper describes one of the first such vehicles, the tracked, 20-ton payload carrier, the Musk-Ox (Figs. 1 and 2). The Musk-Ox was designed and built between July, 1958, and February, 1959, by Wilson, Nuttall, Raimond, Engineers, Inc. (WNRE) of Chestertown, Md., specifically to meet the functional requirements for a muskeg vehicle laid down by Imperial Oil, Ltd.

WHAT IS "MUSKEG"?

Muskeg, or organic terrain, is the most difficult transportation barrier in northern Canada. It cannot be simply defined, although it can be effectively classified. The term "muskeg" denotes organic as opposed to mineral terrain, the physical condition of which is governed and modified by the structure of the contained peats, the living surface vegetation, the mineral sublayer, and topography. In addition to these physical characteristics, either a linear, areal, or cubic dimensional property must be considered, depending on the type of task to be accomplished.

When N. W. Radforth began his studies on the subject of "muskeg" about 15 years ago, he found that the term had become a generic one, used to describe a wide range of terrains found in the poorly drained Canadian northland and the peat bog areas of the world in general. Accordingly, he finally defined "muskeg" simply as organic terrain. (Ref. 1). By this definition a large part of northern Canada and northern Russia may be classed as muskeg, along with the peat areas of Scotland, northern Germany and Poland, and much of the marshy, forested areas of such northern states as Michigan and Minnesota.

In general appearance muskeg, according to the foregoing definition, may vary in all conceivable combinations of organic components from a super-saturated flat grassy or mossy bog over pre-cambrian bed rock to a 100% slope covered with 40 ft trees standing on a moss floor a few inches deep over a saturated clay sublayer. Depths commonly vary between 1 and 60 ft. The Radforth (Ref. 1, 2, 3, 4) classification of muskeg lists nine coverage classes which are commonly used in combinations of three to describe a given muskeg. In addition, he lists 16 topographic contours and 16 features of surface peat constitution. Obviously, the varieties of organic terrain are myriad.
Among the many meanings developed for the term "muskeg" over the years since the north country was first explored are the formal specifications based on the botany of the situation as detailed in the foregoing paragraphs. Originally, however, it seems to have referred more specifically to those ponds and lakes which over the centuries have been grown-over and filled-in by encroaching vegetation. Such grown-over lakes are areas of soft organic material, very wet, and very weak in load supporting strength. They are readily visible from the air throughout much of Canada. It is these marshy, filled ponds and similar larger drainage basins which present the ultimate problem to the vehicle designer. The "lesser" types of muskeg can be traversed by many low ground pressure tracked vehicles. Conventional off-road wheeled vehicles are, except in extremely rare cases, completely immobilized by 6 in. of muskeg.

Much muskeg is underlain by permafrost which, in the far north, is sometimes within striking distance of the surface. In these places vehicles which can tolerate sinkages of several feet may operate on the permafrost rather than the muskeg, even in late summer. In most muskeg areas, however, the permafrost, when it exists, quickly recedes, under repeated passes, to depths where it cannot be utilized by practical vehicles.

PRESENT ECONOMIC SIGNIFICANCE OF MUSKEG

Muskeg occurs in various difficult forms over an estimated 320,000,000 areas in Canada. Of the 500,000,000 acre Western Sedimentary Basin, which is the area of current interest to oil operators, 125,000,000 acres are muskeg covered. That is 25% of prospective oil land in Canada is muskeg covered.

In its search for oil reserves since 1947, the industry has cut approximately 180,000 miles of trails for exploration purposes. Geophysical crews have profiled over 250,000 miles using those trails, at an estimated cost of $150,000,000. The cost of deep tests following geophysical work in muskeg areas is approximately 2 1/2 times the cost of similar tests at plains locations. Part of the increased cost can be traced to expensive transportation over muskeg. The transportation charges for a single test well have been as high as $300,000 or 30% of the total cost. Of the $415,900,000 projected final exploitation cost of the Pembina field about $25 - 30,000,000 are directly attributable to muskeg.

The incentive to improve the effectiveness and efficiency of over-muskeg transportation is obvious.

OPERATIONAL BACKGROUND

Until recently successful overland transport of any magnitude in muskeg was limited to the winter, when the terrain was completely frozen. By clearing away trees and scrub and consolidating any insulating snow cover, so that the piercing cold can rapidly freeze the muskeg beneath, it is possible to make relatively economical snow roads which will support high axle-load truck traffic for two to four months of the year. The muskeg transportation problem is thus concerned primarily with the eight to ten months when this technique does not work.

Studies and increasing field experience have demonstrated that, for the type of oil field development operations presently facing the industry, special, high mobility, muskeg vehicles offer more economical production in the summer months than any combination of less mobile vehicles and special trails to suit them. (Ref. 5)
There are both legal and economic reasons for desiring the capability to work year-around in muskeg country, particularly for the oil industry. Alberta law, for example, requires certain steps in the exploitation of a mineral leasehold within limited periods of time. If an area shows promise, these laws usually dictate "crash" programming with large crews and large equipment budgets during the short season, and layoffs and idle capital equipment during the remaining eight to ten months. There are obvious advantages in balancing the load a little better by learning to work throughout the entire year.

At this moment, with the world oil picture running to surpluses, economic pressure for increased production is not great. There are, consequently, those who feel that the solution at this time is through changes in the laws to permit development to proceed more slowly, with smaller crews working only during the winter months. The long term solution, however, must come through technological advance.

Although the capability to operate continuously will require some special and costly equipment, the net overall savings due to greater usage of other highly capitalized equipment will, in general, fully justify the added transport equipment costs.

THE VEHICLE PROBLEM

The more difficult muskeg areas are particularly troublesome to off-road vehicles primarily because, except when frozen, they have practically no load bearing strength as compared to other off-road terrains. In the really bad areas, which govern "go, no-go" ability, the muskeg will not support large loads except with great sinkages, and even then only at relatively low nominal unit pressures. While not quite as difficult in this regard as some of the bottomless, floating marsh areas of Louisiana in which the oil industry has learned to work, the muskeg covers such a vastly larger region that it constitutes a problem of another order of magnitude. Over-the-marsh transportation in Louisiana is concerned almost exclusively with moving geophysical exploration parties and similar light loads. Once it is decided that a marsh area is worth drilling in, the present normal procedure is to build short roads in to it from the existing road net, or to dredge equally short canals in from the vast net of drainage canals to be found in that same area. The problem of moving drill rigs and other big loads has simply not had to be solved on a strictly over-the-marsh basis. Muskeg sites to be worked may be as much as 150 miles from usable roads.

The problem cannot be bypassed if serious year-around development in muskeg areas is the goal. Muskeg transport must deal with tonnage movement.

DESIGN BACKGROUND

The lead in developing suitable off-road transport for muskeg country has been taken by the Canadian oil industry. Despite the military importance of overland transport capability in so large a proportion of the North American and Eurasian land masses, neither the U.S. nor Canadian army vehicle development agencies have yet really come to grips with the problem.

This is not to say, however, that nothing useful to the solution of the problem was available from military sources. The fundamental vehicle design concepts exploited in the development of the Musk-Ox had been extensively researched over a period of over 10 years prior to the opening of our present story, all with U.S. and Canadian army research and development funds. This
research has gone on since the end of World War II in many places and many climes, and resulted in many, many reports. It has also resulted in the growth of several elaborate and competent laboratories; in the United States, the Army Mobility Research Center at Vicksburg, Miss., and the Land Locomotion Research Laboratory in Detroit; and in Canada, the Vehicle Mobility Laboratory of the Defence Research Board, at Valcartier, Quebec. The results of all this research, although reported and publicized within various army groups, have had singularly little impact upon the development of military vehicles.

One of the major concepts which, although historically it dates from the turn of the century (Ref. 6), was most insistently pressed in the research work was that of steering tracked vehicles by articulation rather than by skid steering, (Ref. 7 - 9). Other important concepts studied, elaborated, and propagandized by the research are: the relationship of the performance of a vehicle to the loads it places on the soil and to soil strength; (Ref. 8) the "bellyless" vehicle, which offers a minimum of nontractive surface to be hung up on; (Ref. 8, and 9) and most recently and perhaps most important, proper scale or dimensional relationships. (Ref. 10)

The important practical result of the latter is the clear indication that natural terrains (whether snow, muskeg, sand or ordinary agricultural soils) may be expected to exhibit greater strength, the greater the depth from the surface at which they are sampled. There are, of course, the odd areas, such as floating marshes, where this obviously is not true. The long history of the formation of the organic components of the muskeg does lead to this conventional type of strength distribution, however.

The interesting consequence of this strength distribution, taken together with other dimensional reasoning, is that if the size of a vehicle is doubled in all its linear dimensions, including its tolerance of sinkage, its nominal unit ground pressure may also be doubled without decreasing the level of performance of the larger machine as compared with the smaller. This point has far reaching implications not only in the design of vehicles for muskeg, but also for other weak terrains.

Fundamentally, it means that although very small vehicles, to be successful, must have extra-low ground pressures, vehicles as they get larger do not have to maintain the same low ground pressures. They may be designed for increased nominal contact pressures without reduction of relative performance. The "increased" pressures may not be intrinsically high, but there is considerable practical difference between a ground pressure of 0.5 psi and one of 3 or 4 psi. The latter is still a very low ground pressure, but it is a feasible target figure for large vehicles, whereas the former is not.

Imperial Oil interest in muskeg transportation actually dates from about 1947, when development began on the first tracked vehicles for geophysical survey work in muskeg. In 1957, after a survey of existing practical know-how and mobility research findings, Imperial decided that a tonnage-carrying vehicle for muskeg crossing was "in the cards." At this point they called on WNRE. WNRE agreed to undertake the project, and feasibility studies were conducted as the first step. These studies resulted in specific recommendations along the lines of the present Musk-Ox.
From the beginning it was decided to attempt a bellyless, low ground pressure machine steered by means of controlled-joint articulation. At the time that this basic decision was taken, there were in operation only three tracked vehicles steered by articulation, plus one interesting tracked-tractor/powered-tracked-trailer muskeg-going combination which has since lead by its own logical sequence of development to another type of articulated muskeg transporter rated for a 10-ton payload.

The first of the articulated-steer tracked vehicles was the well-known Tucker Sno-Cat (Fig. 3). The articulation in this case was in terms of trucks underneath a single chassis steered more or less as a four-wheel-steer wagon might be steered. The principal advantage of articulated steering is simply that turning the vehicle does not call for applying the brakes on one track while, at the same time, requiring extra tractive effort from the other track to develop steering forces. This is a particularly dangerous procedure in terrain that may already be overstressed by the mere presence of the vehicle.

This advantage accounts for much of the success of the Sno-Cat as a snow vehicle. The near complete freedom of each track unit to perform as an individual rather than as parts of a unified vehicle (deliberately incorporated in the Tucker design) has not been an unmixed blessing, however, and is not found in any of the other vehicles. Basically, it does not fully exploit the "train-effect" whereby each unit is so constrained that it cannot fail as an individual but rather must fail mobility-wise, if at all, as part of a complete, single machine.

The second articulated tracked vehicle in operation in 1958 was the Canadian Army Rat, an "in-house" development by the Directorate of Vehicle Development in Ottawa (Fig. 4). The Rat is a 600-lb carrier designed for use in Canada's snow country. It is bellyless and is steered by articulation of two "train" units (joint-articulation), which is the arrangement we believe most favorable. The articulation is controlled manually by means of cables. In the first experimental rig there was an engine on each unit.

This "lash-up" proved highly mobile in the deep, soft snow of the northern Canadian tree-line country, which had hitherto been impassible to small vehicles, excepting such specialized, impractical, nonload carrying devices as motorized toboggans. As a result of this success the Canadian government undertook an extensive development program on the device with Canadair Ltd., in Montreal. (Ref. 11)

The third articulated tracked vehicle operating in 1958 was the Polecat, a WNRE conversion of two World War II Weasels (Fig. 5). This vehicle was powered by a single engine mounted in the rearmost of two "train" units. Power for the front tracks was transmitted to the front unit through the center of the steering joint. This joint, as it turned out, was a scale model of the Musk-Ox joint. Steering was effected by means of a servo-controlled hydraulic system.

The 6-ton gvw Polecat demonstrated better performance in the snow country than the original Weasel, which had stood for the previous 14 years as the Army's standard of comparison. Maneuverability, ride, and side-slope performance of the Polecat were all better than for the parent vehicle. Towing and mobility performance were particularly impressive. The Polecat was able to maintain speed in deep snow with a relatively high towed load, even while maneuvering violently. It was demonstrated that a theoretically equivalent skid-steered vehicle could approach its performance only while going straight ahead,
and lost headway and frequently became immobilized when a turn was attempted. This behavior clearly reflected the additional tractive loads imposed by skid steering upon the already severely loaded terrain.

The fourth vehicle of interest, at the time, was the Nodwell powered, tracked trailer which was successfully moving 2-4 ton loads in the muskeg when operating behind a Nodwell tracked Scout Truck (Fig. 6). While not fully capitalizing on the principles either of articulated steering or of train operation, the combination derived a little advantage from each. For example, the skid-steered tractor applied tongue forces to steer the trailer. Thus, the trailer continued to work with full effectiveness during a turn, even though the tractor did not. Also, each unit was free to pitch as an individual thereby failing to provide the ride and mobility advantages of a long coordinated unit. The coupling did, however, add to the mobility of the combination in those instances when one unit was on a firmer footing than the other.

After review of the existing articulated tracked vehicles, and of the elements which might be brought to bear on the muskeg transport problem, Imperial Oil had the Centipede test rig built (Fig. 7). Two Nodwell powered, tracked-trailer chasses were coupled by means of a WNRE designed articulating joint similar to that of the Polecat. The resulting two-engine machine demonstrated the soundness of the overall principle for muskeg operation. Upon the Centipede's success as a test rig (not as a vehicle), Imperial Oil commissioned the design and construction of the first Musk-Ox.

The Musk-Ox concept was finalized and detail design was begun by WNRE in July, 1958. The Musk-Ox was running in shop trials by early February, 1959, and left the WNRE shops for Canada the first week in March, 1959.

OVERALL DESIGN OF MUSK-OX

Once the decision to undertake the Musk-Ox was made, a survey was conducted of the kinds, sizes, and shapes of load to be moved through the muskeg.

There are two possible approaches to moving wildcat drilling rigs to muskeg or other adverse terrain locations. A specially modified rig composed of units not heavier than a selected maximum can be used. This has been accomplished in pieces as small as 4000 lb for transportation by helicopters and in 10-ton pieces for transportation by smaller tracked vehicles. Alternatively, a special vehicle can be built to carry standard rig components. Rig-up and tear-out time are shortest with the standard rig and greater hole depth can be accomplished when necessary.

Imperial Oil chose to develop a transporter for the standard rigs used in the western sedimentary basin of Canada. These rigs sometimes contain components weighing up to 31 tons. Usually, however, rigs with a maximum single piece weight of 23-25 tons are used. At most, only two loads per rig move need exceed weights of 18-20 tons. The remaining components, supplies, and housing to a total of about 600 tons can be marshalled into 20 ton or smaller loads.

On this basis, a nominal 20-ton payload capability was specified by Imperial Oil as the cargo capacity of the Musk-Ox. Although experience has since indicated the feasibility of building still larger machines for muskeg service, we were not without some fears in the beginning. The minimum (20 ton) was accordingly accepted as the normal maximum load for design purposes.
Volume and area requirements for drilling support could be met by a flat bed 24 ft x 8 ft, and it was basic that the machine be capable of transporting drill pipe and casing 30-40 ft in length.

Successful experience in the muskeg with light, 1.5 - 2 psi vehicles used in geophysical survey work, expanded in accordance with the research results, indicated that a vehicle physically the size contemplated might be expected to exhibit reasonable mobility at a nominal unit ground pressure of 3 - 4 psi. "Bellyless" construction was a part of the concept from the beginning.

Distances over which tracked vehicles might be expected to operate were up to 150 miles. The most common maximum route lengths were judged to be in the 50-75 mile range. Muskeg terrain is rough as well as soft and, consequently, practical average speeds are low. A 50-mile traverse in 10-12 hr over severe terrain conditions was considered to be adequate. Required top speed was, therefore, 10-15 mph.

The configuration which was developed in these early stages was but little changed as detailed engineering proceeded. The outline drawing (Fig. 8) condensed specifications and photographs (Figs. 1, 2, 9 and 10) of the final configuration accordingly are appropriate at this point.

As will be seen, the Musk-Ox is approximately 50 ft long. Overall width was held to 10 ft to facilitate moving it over the roads (via easily obtained permits) and to simplify rail shipment. The engine, transmission, winch, cab, and fuel are carried on the front unit. Power is transmitted through the narrow belly (only 16 in. between tracks) to rear sprockets on each unit. Power for the rear unit is transmitted through the center of the joint.

Although light weight was an objective throughout the design, it was necessary to tread cautiously. Neither funds nor time were available for either an aircraft design approach, or any extensive "cut and try." As a result, experience has revealed some over-design here and there (as well as a little under-design). All-out light weight was also defeated in some instances by our necessary concentration on using existing commercial parts wherever possible in order to facilitate design and construction, to minimize development problems and costs, and to make field maintenance easier and less costly.

The final weight of the first vehicle, all-up, ready to load, and including many husky field additions (such as cab guards, live tail roll, a winch cage, and the like) is approximately 30 tons. Final, full-load nominal unit ground pressure, based upon hard ground, track contact length (as is only proper for nominal figures) is 3.4 psi. Savings of as much as 5 tons in curb weight presently appear possible for future Musk-Oxen.

Specifications are listed in the Appendix.

**CHASSIS**

The frame of each unit consists of a welded low-alloy (SAE 950) steel backbone, with deck frames and suspension axles cantilevered from it (Fig. 11). The entire load is carried through 4 stub axles on the front and 6 on the rear, each with a two-wheel bogie. The wheels are connected to each walking beam through a supplemental air suspension. (As far as the authors are aware, this is the first successful application of an automatic air suspension to a tracked vehicle.)
The two units are connected through a two-piece, gimbal-ring type of joint permitting both pitch and roll freedom between the units about axes within the joint (Fig. 12). The joint angle in the steering plane is positively controlled by a pair of double-acting hydraulic cylinders. The driveline passes through the center of the joint via a pair of Spicer 22 1/2 deg 1700 series automotive universal joints, short-coupled on a splined shaft. The overall joint geometry is so arranged that the transmitted shaft rotation is at constant speed regardless of roll, pitch, or steering angles. Fig. 13 illustrates to some extent the degree to which the machine can conform to the terrain via the joint freedom. (No, she was not "stuck" here.)

Single, split, cast-magnesium alloy road wheels are mounted to standard Timken trailer hubs and spindles. After some grief in the field with the standard trailer axle seals originally fitted, the hubs have been refitted with seals more in keeping with their semi-submerged operation (Fig. 2).

Special, smooth, 20 ply nylon tires, built in an aircraft tire mold, are used. These tires are 30 in. in diameter and 9 in. in section width, and are operated at 120 psi. Punctures have not been a serious problem, and tread wear has been practically unmeasurable in the first 3000 miles.

SUSPENSION DETAILS

The layout of a single bogie is illustrated in Fig. 14 and of the automatic air-suspension air system in Fig. 15. The suspension uses General Tire 14-in. air pillows at a pressure of approximately 120 psi. Automatic leveling valves on the first, third, and last bogies on each side respond to the 3 deg of freedom in leveling in the fore and after centerline plane. (Although there is theoretical redundancy in fitting three valves each side - 6 valves vs. 5 deg of freedom - this has not caused any noticeable misbehavior in practice.) The pressures in bogies 2 and 4 are governed, by means of a special valve, at the average between the two adjacent bogies on the same side. Adding these additional "conditions" makes the pressure to the five units on a side at all times determinate and the resulting load distribution nearly ideal. This system has functioned without serious difficulty for over a year now. The only problem has been the loss by amputation of an occasional leveling valve actuating arm. On future Musk-Oxen each leveling valve will be totally enclosed in its respective walking beam structure.

TRACK

The Musk-Ox track is of the "band" type, using 52 in. wide, cast-steel grouser bars bolted to rubber-covered nylon-rayon fabric belts especially designed for this job by Raybestos-Manhattan (Figs. 16 and 17). The belts are 8 in. wide and 1 in. thick, and have a breaking strength of approximately 60,000 lb each. Four belts constitute the continuous element of each track. Each belt is in sections of approximately 12 ft, joined by long diagonal splices which cross a number of grousers.

This field repairable feature has proved useful, for a section of belt has occasionally been punched-out by a stump or sharp rock coming between the grousers. Despite this, belt life has been good. After over 3000 miles of rugged over-the-trail, through-the-muskeg, uphill, downdale operation, approximately 75% of the original belts are still in use. Some, in fact, appear to have at least half of their life left.
The four-belt construction has, with only one "freak" exception, prevented a belt failure of any sort from immobilizing the vehicle. Experience has demonstrated that failure of a single belt does not stop the vehicle. Failures have as a rule been discovered only after the machine has reached its terminus and has been hosed-down for general maintenance and inspection.

The fabric-base belt has more "stretch" than is wholly desirable. However, this need not continue to be a major problem. Two alternatives are being explored at the moment: one is the use of belts with steel cable strength members, as used on several current army vehicles; the other is a somewhat "beefier" fabric belt which will continue the spliced section principle which has been proven both satisfactory and valuable.

The 52-in. track shoes are heat-treated cast steel, and weigh 37 lb each. These are bolted to the belts by means of 1/2 in., high tensile bolts with backing plates, or washer plates, on the inside of the belt. Although we have yet to have a grouser bar failure, the original backing plates, of cast magnesium alloy (to save track weight) proved too brittle. They have since been replaced by stamped steel plates. Plans for future Musk-Oxen call for forged aluminum backing plates.

The grouser bar was designed to provide a female guide for the single road wheels, at the expense of some theoretical considerations concerning the alignment of belt tension and tractive forces. The results have more than justified this particular decision. Track throwing has never been even an incipient problem, despite the great length of the tracks on the rear unit. This, of course, is not solely due to the guide design. Articulated steering, and close control of the wide track at both sprocket and idler also contribute to the favorable result.

The track has a rather long pitch, 7 5/16 in., and is driven by double plate sprockets acting on the drive lugs integral with the grouser bars between the two belts on either side of the center road wheel path. Sprocket thrust is so aligned with belt tension as to prevent serious shoe "rocking" on the sprocket.

SPROCKETS AND IDLERS

Particular care was taken in the design of both sprockets and idlers to provide positive spatial positioning of the tracks in all respects at these important points. This, together with the single road wheel path and female guiding system, has proved to be most effective. In the few extreme cases where the road wheels have momentarily run out of the female guide path, they have immediately run back in once the external loading which caused the displacement was relieved by further vehicle motion.

Pneumatic tires were originally fitted on the front idlers but because of the difficulty in changing these in the field, steel sprockets have been substituted on the original machine. Future Musk-Oxen will utilize solid urethane tires for this front idler service. The front idlers are mounted on cranks and the tracks are tensioned remotely by means of hydraulic rams.
Rear sprocket drive was adopted on each unit primarily to prevent accumulation of track slack in the track approach zone. This was considered particularly important because some track stretch under load was anticipated with the fabric belts, and no track tension compensation was planned.

The sprockets were originally of 1-in. 4140 steel plate. These showed rapid wear in the early life of the vehicle, at which time it was operating in more mineral soils than muskeg (for reasons beyond our control). They were replaced after 2000 miles by 2 in. wide, cast, heat-treated Micromel steel sprockets of greater hardness. A minor design change was simultaneously incorporated to make replacement of the sprockets much easier in the field. The replacement sprockets, which are 50 bhn points softer than the grouser bars, have since accumulated an additional 1500 miles without serious wear. The present choice of relative hardness assures that wear will still occur primarily in the now easily renewable sprockets rather than on the grouser bars.

Some difficulty has been encountered with icing of the sprocket drums when snow and air temperatures were just below freezing. On the original Musk-Ox a standard Timken planetary truck axle was utilized for the final drive of each unit. The sprocket drum, necessitated by the double sprocket drive (thought necessary, in turn, to give positive track control), was attached to this by means of the standard wheel bolting flange. The drum was of quite large diameter in order to fit over these standard flanges, and clearances between track and drum were accordingly small. Future Musk-Oxen will have one more tooth per sprocket and a substantially smaller drum. The reduced drum size will be made possible by attaching the drum to the planetary by special means rather than by the standard wheel bolt circle. The drums will have 1/4 - 1/2 in. of low durometer urethane polymer bonded to them to further thwart icing tendencies.

POWER TRAIN

The vehicle is adequately powered with a Cummins NRTO-6 turbocharged 6-cyl diesel engine, faced aft and cooled by an oversized radiator and blower fan. The engine on the original vehicle develops 335 hp at 2100 rpm. It drives forward through a torsionally damped Spicer 1700 series propeller shaft to a remote-mounted Allison CLET-5640 Torqmatic transmission. This transmission incorporates a torque convertor with lockout, a retarder, four speeds in semi-automatic array, and a drop case. Power is taken from the rear take-off on the drop case by a Spicer 1800 series propeller shaft whence it is fed into a Timken SFDD 4600 interaxle differential incorporated in a two-gear drop case made especially for this application by Cotta. This differential can be locked at the driver's option, but is normally open so that all four tracks receive substantially equal torque at all times until the lock-up is called for. Drive out of the rear of the case is on two 1700 series drive lines, one to each of two Timken PR200 axles. The driveline from this point through the joint to the rear-most axle incorporates seven separate shafts.

In addition to the retarder in the transmission, standard truck 16 in. x 5 in. air/hydraulic brakes are fitted at each rear sprocket on the front unit, and a propeller shaft parking brake is incorporated on the front take-off of the transmission drop case. The sprocket brakes can be arranged for operation either together on one pedal, or separately via two foot pedals. The latter arrangement provides minimal steering of the front unit when it is detached from the rear (as for shipment).
Experience with this entire system has been completely favorable except for the axles. Here a standard Timken PR200 axle was utilized (over the loud protests of Timken engineers) despite the fact that the track centerline was some 4 in. inboard of the thrust line for which the axle was designed. The crime was abetted by the fact, since discovered, that the tractive capacity of a proper muskeg track in muskeg is much higher than originally estimated, (Ref. 12).

During the first season's 3000 miles of operation, one planetary unit failed completely and was replaced. In addition, six overhauls were carried out on the four units installed on the vehicle as incipient failures were discovered. A modification has been made in Calgary over the past winter which has solved this problem on the first machine. Future Musk-Oxen will be fitted with Timken PR250 axles having the designed thrust lines on the track centerlines. This will result in increasing the critical bearing rating in the planetary final drive by a factor of approximately 5.

STEERING SYSTEM

Steering is accomplished by hydraulic cylinder actuation of the joint (Fig. 12), as shown schematically in Fig. 18. The cylinders are controlled by means of a hydraulic servo-valve manufactured by the Heil Co. and used on International Harvester earthmoving equipment. It is of the type which meters the oil as the steering wheel is turned and thus "follows-up" without a mechanical connection. The entire steering system has worked without fault. It has also been found to have ideal response and accuracy under all field and yard operating demands. Driver fatigue, a most troublesome condition in even small skid-steered vehicles, is nonexistent in this 100,000-lb gvw machine.

OVERALL PERFORMANCE

The first Musk-Ox is geared for a top speed of approximately 14 mph and a maximum gradeability of 90% with its full payload of 20 tons. Its turning radius of approximately 42 ft is substantially less than its length. The combination of good suspension characteristics and the long effective wheelbase given by the 50-ft overall length of the machine has resulted in an extremely comfortable ride over relatively rough terrain. The rear unit rides much more smoothly than the front so that cargo is well protected. The driver slows down for his own comfort long before he is likely to endanger his cargo.

FIELD EXPERIENCE

The Musk-Ox was delivered to Imperial Oil in March, 1959, after very limited shop trials. Following another brief shakedown period in the environs of Calgary, it was put right into the production line and operated for several months by the producing department of Imperial Oil on actual field jobs. The first, and quite typical, operation on which it was utilized consisted of hauling bulk material to control an emergency encountered during a foothills drilling operation 68 miles from a roadhead. The available route was over a trail which was prepared for winter use by trucks and had deteriorated under spring thaw conditions until only a machine such as the Musk-Ox could use it. The trail was mostly on mineral soils; heavy clays, abrasive sandy materials, mud; and snow. It included grades of 15 - 20% rising in a series of pitches for as much as a thousand feet. Frequent short stretches and one continuous 13-mile stretch of open muskeg made the entire operation impassable to anything but a vehicle designed for muskeg crossing. Furthermore, no earthmoving equip-
ment could traverse the area, much less improve the trail conditions. Overall round-trip time was 18 - 20 hr.

These early operations revealed most of the weaknesses discussed earlier. The emergency nature of the operation, with the consequent 24 hr per day and maximum speed requirement, probably precipitated failures which would not have occurred for many thousands of miles under less arduous conditions.

Toward the end of last year's season confidence in the machine, both mechanically and (particularly) in regard to its muskeg-going ability, led to its use more and more in the manner for which it was originally intended; that is, to go across and through muskeg rather than around it as on the earlier trail operations. In this type of operation the Musk-Ox proved highly successful, regularly moving 15-25 ton payloads through muskeg which the men were actually hesitant to attempt walking in. In the worst stretches the decks were often awash.

Over 3000 rugged miles were put on the vehicle last season, despite its being out of service for repairs and "debugging" for perhaps half the time. During this period it put out approximately 25,000 ton-miles of useful cargo movement. This is not large in relation to truck operations, but we believe it may be some sort of record for really difficult cross country operation.

The authors have been in the off-road vehicle business long enough to have observed two important phenomena: first, that the proponents of any off-road vehicle invariably claim that their machine has never been immobilized; and second, that they no sooner make such a statement than everything begins to go haywire. We suspect a relationship here and will, therefore, refrain from making claims on this score, even though we are tempted.

Suffice it to say that the external performance, the mobility of the Musk-Ox has more than met expectations all along the line. As a matter of fact, its performance in muskeg has been so outstanding that the field crews have on a number of occasions used the Musk-Ox to tow additional equipment through this terrain at its worst. (Needless to say, this did not help the weak axle situation.)

From the standpoint of mechanical performance, the several major problems which were revealed in the first year's operations have been mentioned: axles, wheel seals, backing plates, idler tires, sprocket wear, and the rest. Experience with all other parts and components have been entirely favorable.

The Musk-Ox was placed in the shop in Calgary last winter for some minor refinements and correction of those major items remaining at the end of last year's season. It is now back in the field again. It is believed that the development which has gone into the machine as a result of its extensive practical field usage has shaken out the "bugs," and that they are all now well under control.

The operations have convincingly demonstrated that vehicles of this general configuration and size are feasible both mechanically and economically. An economic evaluation of the performance of the Musk-Ox in comparison to light aircraft came about as a result of an emergency operation in the Brazeau River area of Alberta. A wildcat drilling operation under way there threatened a blowout and required considerable additional mud weighting material to bring it under control. The Musk-Ox was pressed into service on this operation as was one of the company's light planes (Otter) which could land at the nearby personnel-
emergency airstrip (normal adjunct to any drilling operation in the bush). The Musk-Ox had the misfortune to experience its first axle failure during this "flap" and so did not cover itself with glory. However, analysis of the performance of both the aircraft and the Musk-Ox in this particular operation (where air distance was less than one-half trail distance) by company airlift proponents indicated that the Musk-Ox while operating had delivered more useful cargo per day for less operating cost and less capital investment than the aircraft. The picture might well change if an airstrip capable of accommodating larger aircraft were built. However, it must be remembered that gains in operating cost would be offset by additional capital charges for the larger aircraft and the more elaborate air strip.

THE FUTURE

The technical and operational successes of the Musk-Ox, while they demonstrate the feasibility of satisfactory transport in even the worst muskeg areas, do not mean that the Musk-Ox is a cure-all. The initial cost of tonnage carrying special muskeg vehicles (in the quantities likely to be required) is of the order of $4,000-6,000 per ton of capacity that is, high; and there appears to be little that can be done to reduce them. First-class components and first-class workmanship are essential. A machine the size and complexity of the Musk-Ox can fail in so many different ways that only by being most careful about everything can a reasonable life expectancy, availability and maintenance cost be anticipated.

This, of course, means that their commercial use will automatically be restricted to the most unfriendly areas, and to operations where traffic will not justify the expense of even rudimentary road building. And even here the incentives to go into such areas must be great. Fortunately, the Canadian north country and many other areas of the world where the terrain is extremely difficult are becoming daily more economically attractive for development.

The principal immediate requirements for vehicles of this type, however, will remain those of the oil industry. Wildcat drilling, development of proved fields, and construction of pipelines in muskeg and similar difficult terrain all require access to limited areas for limited periods of time. All may profit from this new muskeg capability, if it is properly used.

J. R. White has described overall crude oil production problems in terms of the pressure generated by the size of the oil field on one hand, the pull of the market on the other, and the resistance offered by geographical barriers between the two, (Ref. 13). One of the most important areas where machines such as the Musk-Ox can reduce the geographical resistance will be in the construction of pipelines to collect the output of muskeg oil fields. In this operation there is a premium on straightline capability and little incentive to construct a road for a one-pass operation. A machine the size of the Musk-Ox can handle not only the tonnage movement required for pipeline construction but equally as well a 3-yd dragline, a sizeable ditcher, or even a portable 16-in. pipe mill. (Ref. 14)

From a military point of view, we feel that this development, which although carried forward with private funds, has capitalized on so much military research, also has considerable possible importance, for off-road missile movement for example (Figs. 19 and 20). Thus far the military have not noticeably concurred.
CONCLUSIONS

We can now say that at this moment the muskeg can be tamed, if one is willing to pay the price for proper vehicles to do it. The basic means have been demonstrated. The Musk-Ox in its present stage of development is a satisfactory solution. We consider it the most satisfactory solution presently in the field. There are other machines, of lesser capacity, which have compiled enviable records of performance after having gone through periods of development not unlike that just concluded by the Musk-Ox. The current season's operations is showing what the Musk-Ox is really capable of as a developed machine.

The first Musk-Ox is a success. The next ones will be even better.

* * * * * * * * *

REFERENCES


3. Radforth, N. W. ORGANIC TERRAIN ORGANIZATION FROM THE AIR (ALTITUDES LESS THAN 1,000 FT.) Defence Research Board (Canada), D.R. 95, Ottawa, October 1955.

4. Radforth, N. W. ORGANIC TERRAIN ORGANIZATION FROM THE AIR (ALTITUDES 1,000 TO 5,000 FT.) Defence Research Board (Canada), D.R. 124, Ottawa, February 1958.


REFERENCES (Cont'd)


14. NEW MACHINE CAN MAKE LINE PIPE ON RIGHT-OF-WAY. The Oil and Gas Journal, 15 February 1960.
APPENDIX

Current Specifications

THE MUSK-OX

Carrier, Cargo, Tracked - Articulated, 20-ton net payload

Dimensions

<table>
<thead>
<tr>
<th></th>
<th>O. A.</th>
<th>Front Unit (l)</th>
<th>Rear Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>48 ft - 7 in.</td>
<td>24 ft - 0 in.</td>
<td>24 ft - 2 in.</td>
</tr>
<tr>
<td>Width</td>
<td>10 ft - 0 in.</td>
<td>10 ft - 0 in.</td>
<td>10 ft - 0 in.</td>
</tr>
<tr>
<td>Height</td>
<td>10 ft - 2 in.</td>
<td>10 ft - 2 in.</td>
<td>4 ft - 6 in.</td>
</tr>
</tbody>
</table>

(1) Vehicle may be separated into two units for shipping. Front unit can run and maneuver under own power. Rear unit is unpowered when disconnected.

Weights (W/o special oil field equipment)

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Front Unit</th>
<th>Rear Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light, lb</td>
<td>48,500</td>
<td>26,500</td>
<td>22,000</td>
</tr>
<tr>
<td>Fuel, oil, drivers, lb</td>
<td>1,500</td>
<td>1,500</td>
<td>--</td>
</tr>
<tr>
<td>Curb Weight, lb</td>
<td>50,000</td>
<td>28,000</td>
<td>22,000</td>
</tr>
<tr>
<td>Net Payload, lb</td>
<td>40,000</td>
<td>--</td>
<td>40,000</td>
</tr>
<tr>
<td>Gross Weight, lb</td>
<td>90,000</td>
<td>28,000</td>
<td>62,000</td>
</tr>
</tbody>
</table>

Chassis

Welded low alloy steel tubular backbone construction ("bellyless")

Side slope ability: Fully controllable on 40% side slopes

Vertical obstacle climbing: 26 in.

Trench crossing: 10 ft approximate

Angle of approach: 35 deg

Angle of departure: 70 deg

Power Train

Engine: Cummins Turbocharged Diesel - NRTO-6, 375 hp at 2100 rpm, 12/24 v electrical system, heavy-duty air, oil, fuel cleaners, dry sump lubrication, Cummins special cold start system.

Cooling: Full load at ambient 110 F.

Transmission: Remote mounted Allison Torqmatic CLBT-5640 with high gear lock-out, hill retarder, integral drop case; 4 speeds forward, 2 reverse; forward reduction range: 11.1/1 to 0.67/1.
Inter Unit Differential: Timken SFDD 4600 in special two-gear Cotta drop case.

Axles: Timken PR-250 planetary 68 in. tread, 16.65/1

Sprockets: Double 2 in. 4140 hardened steel plate, 11-teeth, 7-5/16 in. pitch, rear drive on both units. Split for field renewal

Drive Line: 1700 and 1800 Series Spicer

Brakes: Torqmatic hill retarder; dual 16-1/2 x 5 in. air/hydraulic brakes on each front unit sprocket (controllable separately at driver's option), transmission-mounted parking brake.

Fuel: Diesel, 220 gal (U. S.) capacity.
Range: 100-200 miles. (Deck on fore unit arranged for ready carriage of four - 55-gal drums of fuel. Air fuel-transfer probe supplied.)

Both units powered from single, front-mounted engine at all times, through inter unit differential, which may be locked at driver's option.

Full Load Performance:
Gradeability: 90%
Top Speed: 15 mph

Tracks
52 in. wide; cast heat-treated, manganese steel track shoes on four 8 in. x 1 in. nylon/rayon reinforced rubber belts, with forged aluminum alloy backing plates; pitch, 7-5/16 in.; belts individually renewable in (approx.) 12 ft sections.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track area, sq. in.</td>
<td>29,000</td>
<td>11,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Area w. 10 in. sinkage, sq in.</td>
<td>43,000</td>
<td>18,000</td>
<td>25,000</td>
</tr>
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</table>

Nominal Unit Ground Pressure

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb weight, psi</td>
<td>1.7</td>
<td>2.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Full load, psi</td>
<td>3.1</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Full load with 10 in. sinkage, psi</td>
<td>2.1</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Track tensioning by hydraulic rams on swinging front idlers.

Suspension and Running Gear

Five walking beams each side, each carrying one leading, one trailing arm, air suspended to beam via 1/2-in. General Tire air pillows; automatic leveling and load distribution; 13-in. wheel travel from full bump to rebound.
Road wheels: Single 9.00-15 smooth, 20 ply nylon tires at 120 psi; mounted on split magnesium wheels, Timken axle stubs. (Tire inflation from vehicle air system.)

Steering

Full hydraulic actuation of articulating joint between units. Hydraulic followup.

Pump: Pesco, 2000 psi, 55 gpm

Valve: Heil

Cylinders: Vickers 6 in. x 21 in. stroke

Turning radius: 42 ft

Cab

Insulated aluminum cab, seat two, full sleeper bunk, two dome lights, hot water heater, four electric windshield wipers, two electric defroster fans, four roof vents, Edwards double sliding windows in doors (tinted glass optional), two electrically heated mirrors, air horn.

Controls: Ross 26-in. steering wheel and column

Two - Bendix-Westinghouse air brakes with crossover

Foot throttle

Hand throttle

Transmission range selector

Transmission dynamic brake actuator

Parking brake

Compression release

Lights

12-v electrical system. Flood/head lights, full clearance lights, turn signals, brake lights; two cargo deck/trouble flood lights on rear of engine cover.

Cargo Provisions

Net payload, normal: 20 tons

All carried on single, flat deck 2½ ft x 8 ft-4 in. Casing up to 40 ft may be carried with special front bunks.

Cargo deck: 2-in. fir, with tie down points each 2 ft along both edges. 5½-in. normal loading height

Cargo gear: Tulsa model 3½ winch with 325 ft, 3/4 cable, one capstan. Hydraulic drive. ¾-in. gin poles stowed alongside deck. 6-in. rear cargo roller. Provision for leading winch cable forward over tracks on either side of backbone.
Captions for Illustrations

Fig. 1 Twenty-ton payload carrier, Musk-Ox
Fig. 2 Musk-Ox negotiating short stretch of weak muskeg
Fig. 3 Tucker Sno Cat, first practical, tracked vehicle to utilize articulated steering
Fig. 4 Early prototype Canadian Army Rat, first practical joint-articulated tracked vehicle
Fig. 5 First Polecat, with joint-articulated steering under hydraulic servo control
Fig. 6 Scout truck and powered trailer, geophysical support vehicles which in combination give good muskeg performance
Fig. 7 Centipede test rig built to test the joint-articulation principle in muskeg, prior to beginning design of Musk-Ox
Fig. 8 Musk-Ox 20-ton muskeg carrier
Fig. 9 Musk-Ox loaded on flat car
Fig. 10 Musk-Ox at speed during shop trials
Fig. 11 Musk-Ox frame schematic
Fig. 12 Musk-Ox joint. Front unit is to left
Fig. 13 Musk-Ox joint permits complete roll and pitch freedom of two units about axes within joint
Fig. 14 Musk-Ox bogie assembly
Fig. 15 Musk-Ox air suspension schematic
Fig. 16 Musk-Ox band track, on sprocket
Fig. 17 Inside of Musk-Ox track, with original cast magnesium backing plates
Fig. 18 Musk-Ox hydraulic steering schematic
Fig. 19 Proposed 60-ton carrier Muscleman, for off-road movement of missiles
Fig. 20 Muscleman is less of "jump" from Musk-Ox than Musk-Ox itself was from its predecessors