Observations of Ice-Cover and Openwater-Lead Formation
along the Fort Peck Reach of the Missouri River

Robert Ettema

Iowa Institute of Hydraulic Research
The University of Iowa, Iowa City, IA 52242, USA
robert-ettema@uiowa.edu

and

Leonard Zabilansky

US Army Corps of Engineers
Cold Regions Research and Engineering Laboratory
Hanover, NH 03752, USA
ljzab@crrel.usace.army.mil

Reported herein are observations of ice-cover and, relatedly, openwater-lead formation along the Fort Peck Reach of the Missouri River, Montana, during two winters; 1998-99 and 2000-01. Openwater leads along the Fort peck reach seem to resist being frozen over during much of winter, and recur at several specific locations. The leads vary in area, but commonly are about 200ft or more in length, and average about 10ft to 30ft in width. Lead formation is explained herein relative to ice-cover formation along reservoir-regulated rivers conveying substantial flows during winter along channels of sinuous and sinuous-braided morphology. The environmental significance of such leads is discussed briefly.
1. Introduction
This paper presents qualitative observations of ice-cover and openwater-lead formation along Montana’s Fort Peck reach of the Missouri River. The observations were made during the winters of 1998-99 and 2000-2001. They are not fully complete, but provide useful glimpses into winter channel conditions along the Fort Peck reach. Though the motivation and main focus of the observations were the effects of river ice formation on alluvial-channel stability and riverbank erosion, the observations were an opportunity to monitor other features of the winter environment along a complex plains-river channel. A striking feature was the formation of openwater leads at similar channel locations.

The 1998-99 set of winter observations is fully documented by Zabilansky et al. (2000), who conducted a comprehensive measurement program that produced detailed data on flow, bathymetry, and ice conditions for five sites along the Fort Peck reach of the Missouri River. Ettema (2001) subsequently provided further observations of channel conditions during the winter of 2000-2001. Simon et al. (2000) discuss the broad geomorphic issues associated with the reach.

Both sets of winter observations sought insights into, and confirmation of, processes whereby frigid-winter conditions (notably, river ice, frozen soil, river flow, and snow) may affect the river channel along the Fort Peck reach of the Missouri. The observations focused on five sites along the downstream half of the reach. Of interest were river-ice effects on the following concerns:

1. Stability of riverbanks;
2. Stability of channel-thalweg alignment;
3. Performance of riverbank and channel stabilization methods; and,
4. Recurrence of openwater leads at specific locations.

Concern 4 is the focus of the present paper. An intriguing feature of the Fort Peck reach observed during the winter of 2000-01 was the winter-long persistence of openwater
leads at similar channel locations. For example, the lead depicted in Fig. 1 formed along the flank of a small island in the river.

The persistence of such leads during winter is readily explainable. However, their recurrent formation at specific locations is intriguing, and moreover likely to play significant a role in the river’s winter environment. This paper discusses the recurrence of the leads, and ponders their likely environmental (bathymetric and water-quality) significance.

Fig. 1. An openwater lead flanking an island in the sinuous-braided reach of the Culbertson site, February 19, 2001; RM 1621, Missouri River. Highway 16 Bridge is in the foreground.

2. Background
Several concerns prompted the need for the observations during the winter of 1998-99. The Omaha District of the U. S. Army Corps of Engineers (USCAOE-Omaha), which has
long-term interests in the overall behavior and relative stability of the Missouri River, wished to determine whether and how channels along the Fort Peck reach of the Missouri River altered during winter. It was hoped that the observations would assist USACOE-Omaha in its efforts to mitigate possible adverse effects of flow releases from Fort Peck Reservoir during winter. In particular, the observations would be of possible use for winter operations of Fort Peck Dam. That knowledge is needed as USACOE-Omaha considers enhancements to the Corps’ Current Water Control Plan (CWCP) for the river.

Moreover, the observations would help USACOE-Omaha better understand the wintertime performance of channel and riverbank stabilization methods that it recently installed at a site in the Fort Peck reach and at other sites along downstream reaches of the Missouri River. The observations would be of use in further design and deployment of the methods.

Impetus for the observations also was provided by immediate concerns facing farmers and small communities along the Fort Peck reach. Extensive riverbank erosion along several portions of the reach continues to diminish productive irrigated cropland along the river, and a high proportion of pump sites along the reach experience sedimentation difficulties. A frequent remark by people living along the reach is that the bank erosion and pump-site sedimentation processes are especially apparent in early spring when ice departs the reach. Those processes are not unrelated to lead formation, as discussed later.

Information from the study is of use for other reaches of the Missouri River and for other rivers in the Omaha District of the Corps. It is of direct relevance to river engineering activities concerned with issues of channel and riverbank stabilization and optimal reservoir regulation for rivers subject to frigid winter conditions. For example, it has substantial implications for the location of diverse hydraulic structures and navigation-channel maintenance in such rivers.

3. Observation Sites
Winter conditions were observed at the following six sites along the Fort Peck reach:
1. Culbertson water intake and Highway 16 Bridge, RM 1621;
2. Buffalo-Jump Bend, RM 1622;
3. Tveit-Johnson farm, RM 1624;
4. Vournas farm, RM 1631;
5. Mattelin farm, RM 1646; and,
6. Pipal farm, RM 1716.

FIG. 2. The Fort Peck reach of the Missouri River.

Fort Peck Dam is at about RM 1770. The sites extend from the towns of Wolf Point and Culbertson, as indicated in Fig. 2. All the sites, except site 3, were closely monitored during the winter of 1998-99 (Zabilansky et al. 2001). During that winter, channel bathymetry and flow distribution were measured at the sites on four occasions before the ice cover formed, when the ice cover was present, and shortly after the ice cover broke up. Observations were made at all six sites during mid-February, 2001.

1 RM is river mile from the confluence of the Missouri River and Mississippi Rivers.
The Tveit-Johnson, Vournas, and Pipal sites are usefully representative sites of bank erosion. Anecdotal evidence exists of thalweg switching from one sub-channel to another in the multi-thalweg channel at the Mattelin and at the Culbertson sites. A jam occurs on occasional years at the Vournas Farm. These five sites could form a set of monitoring sites. Three of the sites, the Pipal, Mattelin, and Tveit-Johnson sites, appear most prone to the adverse effects of elevated freeze-up, thalweg shifting, and freeze-thaw weakening of bank soil.

4. Physical Setting of the Fort Peck Reach

Much has been written about the physical setting of the Missouri River, including the Fort Peck reach of the river; observations date back to the Lewis and Clark Expedition of 1804-06. Fairly numerous publications document the reach’s flow and channel characteristics, especially in the years following the closure of Fort Peck Dam. Several investigations address concerns about channel-bed degradation along the upper half of the river, subsequent to the river’s closure in 1940 by Fort Peck Dam (notably, USACOE-Omaha 1945, 1952, Pokrefke et al. 1998). Several recent publications (e.g., Simon et al. 1999, Pokrefke et al. 1998, and Wei 1997) describe and discuss channel-stability concerns as well as concerns about riverbank erosion along the reach.

Channel Morphology

The Fort Peck reach of the Missouri River begins at the tailwater of Fort Peck Dam, Montana (RM 1770), and it ends at the headwaters of Lake Sakakawea, retained by Oahe Dam, in North Dakota. The river channel itself is approximately 170-miles-long, and 800ft to 1,200ft wide along the reach. The channel’s average slope over this distance is about 1.6 x 10^-4 to 1.8 x 10^-4.

The closure of Fort Peck Dam in 1940 affected peak flow rates, sediment supply, and channel-bed elevations along the reach. It, thereby, also affected ice formation along the reach. Ettema (2001) summarizes freeze-up and break-up dates for the period 1937 through 2000. Studies of changes in bed elevation along the reach (notably, USCOE-Omaha 1945 and 1952, Wei 1997, Pokrefke et al. 1998) show that the channel bed
degraded over a distance of about 70 river mile immediately downstream of the dam. Near the dam, the average bed level dropped about 6 ft, with drops in bed elevation of as much as 11 ft occurring at some locations along the channel’s thalweg. The consensus opinion is that significant further channel-bed degradation attributable to the dam is not anticipated (e.g., Pokrefke et al. 1998, Simon et al. 1999).

The channel morphology of the Fort Peck reach can be described as sinuous braided. In simple terms, the river channel forms semi-regular beats (in flow area) comprising – a narrowed channel with a single thalweg channel segment, followed by a widened segment with two or more sub-channels and bars, followed in turn by a single constrained channel. Fig. 3 illustrates this channel morphology for the Culbertson site, RM 1621–1622. Its characteristics are transitional between those of meandering channels and of braided channels. At flood flow and sometimes under ice-covered flow, the bars are under water.

An exemplifying temporal feature of the wider sub-reaches is the switching of thalweg position between sub-channels. Such switches can be triggered by several factors, including a large change in flow magnitude, a change in orientation of flow entering the sub-reach, and (as revealed subsequently in the present study) ice-cover formation.

Riverbed Sediment
The sediments comprising the riverbed of the Fort Peck reach are mainly sands with zones of gravel deposit, exposed clay, and silts. In the sub-reach immediately downstream of Fort Peck Dam, the bed sediment is coarser than downstream, and they reflect the overall degradation experienced by the upstream portion of the reach. The sub-reach evidently exhibits bed armoring, whereby the upper surface of the bed is armored with coarser sediment less readily entrained by flow. For the extent of the Fort Peck reach encompassed by sites 1 to 6 (RM 1620 to RM 1717), the riverbed is formed mainly of fine to medium-size sand, with median particle diameter in the range of 0.2 to 0.3 mm.
Fig. 3. The Fort Peck reach of the Missouri River includes numerous widened reaches in which two or more main sub-channels flow around alluvial island (bars), such as illustrated here for the Culbertson site (RM 1621) in 1991. Highway 16 crosses the site.

The sediment load conveyed by the river comprises bedload sediment whose source comprises the eroding riverbanks and shifts in channel bed. Washload sediment, comprising fine silts and clay sediment, originates from riverbank erosion as well as from tributary inflow. The average annual sediment load is estimated to be about $5 \times 10^6$ tons at Culbertson (Simon et al. 1999). The load is about zero immediately downstream of Fort Peck Dam. The sediment load estimate is based on a continuous record of suspended-sediment load was recorded during the years 1958 through 1972 at a sediment-measuring station located just downstream of Highway 16 bridge at Culbertson. About 35% of the suspended load consists of silt and clay sediment; the remainder is sand entrained from the channel bed.
Riverbanks
At some locations along the reach, especially in channel bends, the river has cut quite steep riverbanks. The riverbanks typically are formed of soils having relatively low shear strength, especially low cohesive strength (Simon et al. 1999). The soils typically consist of silty and sandy layers interspersed with clay or silty-clay layers. The occurrence of a layer of sandy or silty soil at the toe or base of riverbanks, makes them especially prone to erosion at some locations. This feature is common at the sites observed.

Flow Characteristics
Flow rate through the reach is monitored continuously by several stage gauges operated by the US Geological Survey (USGS) and by flow release from Fort Peck Dam, which is operated by the USCOE-Omaha. Winter flow rates typically have varied within the range of about 2,500cfs to 22,500cfs, since closure of Fort Peck Dam. The flow record into the reservoir is reported to be 135,000 cfs (USACOE-Omaha 1990); it occurred during June 1953. As extensively documented in several reports (e.g., Simon et al. 1999), of flow regulation in 1940 significantly altered the annual distribution of flow through the reach. The effects of flow release on river-ice formation have yet to be investigated.

Prior to advent of the dam, flows through the reach were at lowest stage throughout winter, the lowest stage occurring usually during the early winter months (e.g., USACOE-Omaha 1990). It was usual for the reach to convey two annual flood flows: one flow in April attributable to snow melt augmented by rainfall and ice-cover breakup throughout the lower elevations of the river’s watershed; and, a second flow, called a “June rise,” caused by snow melt in the mountains. A further flow increase, of lesser magnitude, regularly occurred during October into November.

Once the dam began significantly regulating flow releases in 1941, it reduced the temporal variability of flows in the reach, and it altered the distribution of peak or flood flows in the reach. For the period 1970 through 1995, peak flows usually occurred
during the winter months. The average peak winter flows increased from about 5,000cfs to about 14,000cfs.

Flow releases from Fort Peck Dam generally conform to a water-management schedule for the main-stem dams on the Missouri River. The schedule, called the Current Water Control Plan (CWCP), presently is under re-consideration by USCOE-Omaha. An alternate schedule, called the Preferred Alternative (PA), is favored. The PA schedule would move the peak plan discharges into the spring, rather than having them occur later in the year (Pokrefke et al. 1998). The variations in flow rates between the PA and CWCP schedules are smaller compared to actual variations in annual river flows. Consequently, it is thought (Pokrefke et al. 1998) that implementation of the PA schedule would not substantially alter the present behavior of the Fort Peck reach. The consequences for river ice formation, however, are unclear, as river ice seems not to have been included in the evaluation of the possible effects resulting from the PA schedule. If the PA implies reduced winter flow rates, river-ice may form faster and thicker, as flows would be shallower and convey less heat. On the other hand, ice covers would form at lower stage elevations in the river channel. This conjecture needs further consideration, possibly by means of numerical simulation.

Ice Formation
With Fort Peck Reservoir as the source of flow, the river begins forming its ice cover at several locations considerable distances downstream of the dam. For given weather conditions, the flow rate and temperature of water released from the reservoir, influence where and how ice covers form on the lower Missouri. The river’s sinuous-point-bar and sinuous-braided morphologies ensure that the flow through the Fort Peck reach is well mixed over the flow depth, such that its temperature and thermal energy are practically homogeneous over its depth. Those morphologies also produce substantial variations in flow velocity within reaches, and they provide numerous locations where frazil-ice slush and pans may congest and form an ice cover or a jam that propagates upstream.
Flow rate and temperature of water influence where ice first appears. The higher the flow rate and temperature of flow released into the river, the greater the distance of flow before ice-cover formation begins. Local channel morphology influences where the river actually begins forming its ice cover. The river’s mild slope (about $1.6 \times 10^{-4}$ to $1.8 \times 10^{4}$) and relatively moderate average velocities facilitate the formation of an initial cover of juxtaposed ice pans and floes over most reaches; average velocities at Wolf Point (see Fig. 2) and Culbertson are about 2.3 and 2.0 ft/s, respectively (Pokrefke et al. 1998). At some sections and flow rates, velocities may be high enough (nominally in excess of 6 ft/s) that ice pans get sub-ducted under the ice-cover front, causing a thickened accumulation to develop. The average flow velocities seem not to get that large that a severe freeze-up jam occurs. The velocities are such that frazil slush may accumulate under the cover. On the whole, bulk flow velocities increase upstream, with the likely consequence that cover formation becomes progressively more difficult at upstream locations.

5. Weather and Flow Conditions during Observations

River flow, weather, and ice-cover conditions were recorded during the winter of 1998-99. They were monitored only in approximate terms for the observation period during the winter of 2000-01.

In accordance with the data trends over a sixty-year period, the winters of 1998-99 and 2000-01 appear to have been a fairly normal winter for the reach. A difference between the two winters is that the winter of 2000-01 began with rain in December, which saturated the upper layer of the ground, then was followed by snow. The rain exacerbated riverbank erosion by weakening riverbank soil. The winter of 1999-00 was milder; significant ice formation did not occur on the river during that winter.

Figure 4 is a temporal record of flow releases from Fort Peck Dam during the winters of 1998-99 and 2000-01. The river flow rate was in the range of about 9,800cfs to 9,400cfs during the observation period, February 17 ~ 20, 2001, when observations were taken in that winter. During January, and into early February, the flow rate was in the range of
10,200cfs to 11,800cfs. Tributary flow from the Milk River amounts to less than 100cfs during winter. Corps of Engineers (Monthly Reservoir Operation sheets) reported these flow-rate levels. Fort Peck Reservoir was at its rule-curve reservoir level at the time of the present observations (Corps of Engineers Omaha District, web site).

![Flow discharge through the Fort Peck reach of the Missouri River, Dec. – March for two winters. The discharge values of flow released from Fort Peck Dam.](image)

The air and water temperatures at the Culbertson site (RM 1621) are shown in Fig. 5 for the period Dec. 1998 through April 1999. Water temperature continued at about 0.5°C to 1.0°C while the ice cover was present. It rose steeply once the cover broke up.
6. Observations of Ice-Cover and Lead Formation

The occurrence of openwater leads throughout the reach is attributable to the manner of river-ice formation along the sinuous and sinuous-braided sub-reaches that comprise the Missouri River. The leads appear to form along the flanks and downstream bars and islands where the channel bifurcates into two or more sub-channels. They also occur in patches immediately downstream of freeze-up jams along some river bends. Once an ice cover is formed and somewhat insulates the river, enabling “warm” water (water slightly above freezing) to persist for greater distances along the river downstream of the reservoir whence the water is released.

For the winters of 1998-99 and 2000-01, freeze-up occurred along the river during late December. At the Culbertson, Tveit-Johnson, and Vournas sites, it occurred around

Fig. 5. Air and water temperatures at Culbertson site, RM 1621, Dec 1998-April 1999.
December 20. At the Mattelin and Pipal sites, it occurred on the same day as at Culbertson, but during the evening of December 20, being completed on December 21. Freeze-up can occur somewhat earlier than these dates (Ettema 2001). Usually, the ice cover extended upstream to about 20 miles m of Fort Peck Dam.

The thermal influence of Fort Peck reservoir on ice-cover formation along the reach can be demonstrated quite readily. Prior to construction of the reservoir, the flow entering the channel reach would be at the freezing temperature of water (0°C). An ice cover then potentially could begin forming throughout the full length of the channel. However, when the Reservoir released, say a 3-m-deep flow of 4°C water with an average velocity of 1 m/s and exposed to representative conditions of air at about -20°C, the flow would travel almost 70 miles downstream from the reservoir before it cooled to 0°C. If the initial temperature of the water leaving the reservoir were 1°C, the distance reduces to about 18 miles. Therefore, as the water in the reservoir’s water cools during winter, the ice cover on the river may progress further upstream. By early January, water temperature at the monitored sites (RM 1717 to 1621) was approximately 0.5°C to 1.0°C over the measured flow depth. Ice cover presence drastically reduces heat loss from the water, enabling the water to hold its temperature along the reach, and thereby enabling the leads to persist throughout the two winters. Some border ice growth did cause the surface areas of the leads to diminish, however.

At all the sites, the ice cover formed primarily through accumulation of drifting frazil-ice slush and pans, also skim ice. An important part of freeze up was the formation of border or bankfast ice along riverbanks. Bankfast-ice growth congested flow surface available for ice passage, especially in the wider sub-reaches in which the river flowed through two or more sub-channels, such as at the Culbertson site. At some locations ice did not completely cover the channel; e.g., at the Culbertson site and the upstream end of the Pipal site. At those locations, drifting ice bridged across the upstream end of a sub-channel, leaving an openwater lead. Under continued frigid weather conditions, the leads did not completely freeze over. Under the fairly mild winter weather of the present survey, some leads remained open during the entire winter.
Figs 6a,b illustrate how ice formation typically occurred through sinuous-braided reaches, and how cover formation influenced channel bathymetry.

Two scenarios for alternation of major sub-channel are as follow:

1. A relatively short initial accumulation of drifting ice in sub-channel 1 may diverted drifting ice into sub-channel 2, which then became extensively enveloped by a rough ice cover. Meanwhile, sub-channel 1 remained partially open or subsequently froze over with a smooth thermal-ice cover.
2. A relatively long initial accumulation of drifting ice in sub-channel 1 diverted drifting ice and flow into sub-channel 2, which then became extensively enveloped by a less rough ice cover.

River ice thickness was highly variable. For the winters of 1999-99 and 2000-01, nominal maximum thickness of about 2ft to 2.5ft was estimated from exposed portions of exposed bankfast ice. In some locations the ice was very thin. The cover formed mainly by way of local freeze-up jams and by bankfast-ice growth.

Figure 7 depicts Culbertson site (RM 1621) on February 28, 1999. The ice cover contained a lead in about the same location as observed on February 19, 2001 (Fig. 1), though the lead was somewhat smaller in 1999. A similar reappearance of leads occurred at the Pipal site (RM 1717), as depicted in Figs 8 and 9. The lead was almost exactly the same size for both winters.

Additionally, the flow velocities through the leads, estimated as about 3ft/s, suggest that the flow is well mixed over its depth, and thereby impedes thermal stratification, which could enable ice-cover growth over stationary water.

7. Environmental Significance of Leads
The environmental significance of the openwater leads is not entirely clear, but likely indicate two or more types of influence:

1. Bathymetric; and,
2. Biological.

As indicated in Figs 6a,b, the leads are associated with the location of the channel thalweg. Flow resistance appears to be less through the region containing the openwater lead than along the more heavily ice-congested sub-channel. Consequently, I was noticed during the 1998-99 observations that the sub-channel with the openwater lead deepened
during winter. It subsequently filled back with sediment once the ice cover broke up at the end of winter.

1. When sub-channel 1 remained partially open, or was covered by a smooth cover of ice, the greater flow resistance in sub-channel 2 caused flow to favor sub-channel 1, which then enlarged.

2. When a relatively long initial accumulation of drifting ice accumulated in sub-channel 1, no openwater lead occurred, and the greater flow resistance in sub-channel 1 causes flow to favor sub-channel 2, which then enlarged.

Lead formation is of significance for engineering activities and environmental processes along alluvial rivers subject to frigid winters.

Fig. 7. View of the openwater lead at RM 1621, February 28, 1999. (c.f., Fig. 1)
Fig. 8. View downstream of the openwater lead formed at RM 1717, January 27, 1999.

Fig. 9. View upstream of the openwater lead formed at RM 1717, February 19, 2001.
Cover formation adversely affects water quality (e.g., Prowse 2001). The amount of light that penetrates the river greatly reduces as the ice cover forms and envelops the Fort Peck reach. Also reduced are oxygen levels and nutrient influx to the river. Furthermore, feeding opportunities diminish for birds reliant on fish as part of their diet.

Large sections of the ice cover typically are opaque, owing to the accumulation nature of cover formation and to snow that usually layers the ice cover. Cover formation, therefore, would cause a major decrease in the amount of dissolved oxygen in the water flowing in the river. In addition to diminishing greatly aeration by way of flow mixing over the depth and contact with the air-water interface, algal photosynthesis likely shuts down rather quickly after the accumulation cover forms and becomes snow covered. Prowse (2001) usefully elaborates cover-formation consequences on water quality in the river. The aspect of water quality in ice-covered rivers needs further investigation.

For the moment, though, it is possible to conjecture that openwater leads provide important windows whereby insolation, some aeration and nutrients may enter the water under an ice cover. For ice covered maritime waters, leads and their coastal cousins, polynias, are known to play very significant role for sustaining life during winter. Perhaps, leads such as form along the Fort Peck reach of the Missouri River play a comparably significant role for riverine biota?

8. Concluding Comments
The present set of observations, though essentially qualitative, are significant. They provide some insight into ice-cover and openwater-lead formation along a plains river whose channel morphology is complex. Such observations are quite scarce, and have significance for other plains rivers, such as the Platte River in the U.S. Midwest.

The recurrence of the openwater leads in the same along the river. Their formation evidently depends on the manner whereby the ice cover develops on the river. For the usual winter, the water flow from Fort Peck Reservoir has sufficient heat to inhibit complete freeze-up of the river. The leads have physical and biochemical significance
for water quality and habitat conditions along the Fort Peck reach. More work is need to
ascertain the connections between ice-cover formation, channel morphology and quality
of winter habitat.

8. References

Ettema, R., 2001. Observations of channel conditions along the Fort Peck reach of the
Missouri River: Winter 00-01. Limited Distribution Report 291, Iowa Institute of
Hydraulic Research, Iowa City, IA.

Pokrefke, T., Abraham, D. A., Hoffman, P. H., Thomas, W.A., Darby, S. E., and Thorne,
Waterways Experiment Station, Vicksburg, MS.

aspects // II: biological aspects. ASCE Journal of Cold Regions Engineering, Vol. 15,
No. 1, pp1-33.

Simon, A. Shields, F. D., Ettema, R., Alonso, C., Marshall-Garsjo, M., Curini, A., and
Dam and the North Dakota Border. Technical Report, USDA-Agricultural Research
Service, National Sedimentation Laboratory, Oxford, MS.

USACOE-Omaha, 1945. Report on retrogression observations, Missouri River
District.

USACOE-Omaha, 1990. Aggradation, Degradation, and Water Quality Conditions:
Missouri River Mainstem Reservoir System. Technical Report, River and Reservoir
Engineering Section, Hydrologic Engineering Branch, US Army Corps of Engineers,
Omaha District.

USACOE-Omaha, 1952. Report on degradation observations, Missouri River
District.

prepared for US Army Corps of Engineers, Omaha District, by Midwest International
Inc.

river-ice influences on channel bathymetry along the Fort Peck reach of the Missouri
Cold Regions Research and Engineering Laboratory, Hanover NH.