Mr. Hanlon:

I have been asked by several people that have seen my presentations on the work I am involved with as part of a 5 year project funded by the NSF on the Sustainability of Natural Gas Development, of which hydraulic fracturing is a large part to participate in the March 7 Public Teleconference concerning the EPA SAB Draft Report, and I am writing to you to ask to be included. I attached a PDF of my latest presentation to the GWPC UIC Conference.

Thanks,

Dr. William W. Fleckenstein
Former Interim Department Head, BP Adjunct Professor and PERFORM Director
Colorado School of Mines - Petroleum Engineering Dept.
Golden, CO 80401
SPE-175401

An Assessment of Risk of Migration of Hydrocarbons or Fracturing Fluids to Fresh Water Aquifers: Wattenberg Field, CO

W.W. Fleckenstein; A.W. Eustes; C.H. Stone; P.K. Howell, Colorado School of Mines
Shale development:

- Controversial
- Leakage estimates disputed

This paper provides a fact based estimate of leakage.
For contamination of an aquifer:

During production: 3 independent failures

1. Cemented surface casing
2. Cemented production casing
3. Annular hydrostatic head

During completion, two additional failures

4. Frac string pressure monitoring
5. Annular pressure monitoring
Multiplication rule for independent events:

\[ P = \prod_{n=1}^{n} P(A_i) \]

Migration of hydrocarbons to an aquifer
• 3 independent failures

\[ P = 0.05^3 \]

Probability of hydrocarbon migration

1 event per 8,000 wells.
Multiplication rule for independent events:

\[ P = \prod_{n=1}^{n} P(A_i) \]

Aquifer contamination by during fracturing
- 5 independent failures

\[ P = 0.05^5 \]

Probability of fracturing fluid contamination

1 event per 3,200,000 wells.
Well Barriers

Wellbores have many barriers in place

Barriers may be static or dynamic.

Barriers may be passive or active
Failure is the breakdown of one or more of the various wellbore barriers (casing, cement and hydrostatic pressure of annular fluids) protecting fresh water aquifers during stimulation and production operations.

Catastrophic failure is failure resulting in the contamination of the aquifers or surface. This contamination is detected by sampling of thermogenic or other identified hydrocarbons or fracturing fluids in offsetting water wells or on the surface.
The Wattenberg Field is located near Denver, CO.

Data from 17,948 wells drilled between 1970 – 2013

Wells were classified by construction types.

Possible barrier failures were identified by:

1. Remedial cementing below the surface casing shoe
2. Possible presence of Sustained Annular Pressure

Catastrophic barrier failures were identified by:

1. Thermogenic gas detected in offset water wells combined with barrier failure in an adjacent well.
In the 1970’s, Muddy J was target, with TOC brought 500’ above.

In the 1980’s – mid 1990’s - TOC of the production cement below the top of the Sussex formation.

The Sussex & Muddy J is under-pressured.

The annular fluid hydrostatic head prevents hydrocarbon migration if zonal isolation is not achieved from production cement.

The various historical well designs were accounted for by classifying 7 vertical and 6 horizontal well types in this study.

SPE-175401-MS• An Assessment of Risk of Migration to Fresh Water Aquifers: • Fleckenstein
Historical surface casing setting depths pre-cement remediation.

1970’s shallow surface casing depths were designed the purpose of well control during drilling operations and not for aquifer isolation.
Historical Surface Casing Setting Depths Post Remediation

Historical surface casing setting depths post-cement remediation.

Remedial cementing was necessary to place a second cement barrier in the production casing annulus, to protect the aquifer.

SPE-175401-MS• An Assessment of Risk of Migration to Fresh Water Aquifers: • Fleckenstein
The Niobrara and Codell formations, at an average depth of 6,950 – 7,400 ft TVD, were thought to be unproductive until their “discovery” in the early 1980’s.
Historical production top of cement (TOC) depths post-cement remediation.

Production casing cement tops were brought well above the Niobrara after 2000.
Horizontal Wellbore Construction

CATEGORY 5H WELL DESIGN:
3 BARRIERS

- DEEP 13-3/8" SURFACE CASING
- TOP OF CEMENT ABOVE TOP OF GAS
- LINER OVERLAP 500 FT INTO INTERMEDIATE CASING
- 5,000 FT LATERAL
- ~5,000 FT OF 4-1/2" PRODUCTION LINER CASING (6-1/2" HOLE)
- 6,850' TVD
- 7400' OF 7" INTERMEDIATE CASING (12-1/4" HOLE)

SPE-175401-MS• An Assessment of Risk of Migration to Fresh Water Aquifers: • Fleckenstein
Is Thermogenic Gas Being Discovered in Fresh Water Aquifers?

Catastrophic barrier failures and possible barrier failures in the Wattenberg field.

Thermogenic and biogenic methane detected in Fox-Hills aquifer in the Wattenberg field (Li, et al., 2014)

SPE-175401-MS• An Assessment of Risk of Migration to Fresh Water Aquifers: • Fleckenstein
### Summary of Well Construction Types

<table>
<thead>
<tr>
<th>CATEGORY 1</th>
<th>BARRIERS</th>
<th>BARRIER TYPE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1</td>
<td>HYDROSTATIC PRESSURE</td>
<td>VERTICAL WELL, SHALLOW SURFACE &amp; TOC NOT ABOVE TOP OF NIOBRARA</td>
</tr>
<tr>
<td>C2</td>
<td>1</td>
<td>HYDROSTATIC PRESSURE</td>
<td>VERTICAL WELL, SHALLOW SURFACE &amp; TOC NOT ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C3</td>
<td>2</td>
<td>PRODUCTION CASING + HYDROSTATIC PRESSURE</td>
<td>VERTICAL WELL, SHALLOW SURFACE &amp; TOC ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C4</td>
<td>2</td>
<td>PRODUCTION CASING + CEMENT COLUMN</td>
<td>VERTICAL WELL, SHALLOW SURFACE &amp; TOC ABOVE SURFACE CASING SHOE</td>
</tr>
<tr>
<td>C5</td>
<td>3</td>
<td>SURFACE CASING + CEMENT + HYDROSTATIC PRESSURE</td>
<td>VERTICAL WELL, DEEP SURFACE &amp; TOC NOT ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C6</td>
<td>3</td>
<td>SURFACE CASING + CEMENT + PRODUCTION CASING</td>
<td>VERTICAL WELL, DEEP SURFACE &amp; TOC ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C7</td>
<td>4</td>
<td>2 CASING STRINGS + 2 CEMENT COLUMNS</td>
<td>VERTICAL WELL, DEEP SURFACE &amp; TOC ABOVE SURFACE CASING SHOE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CATEGORY 1H</th>
<th>BARRIERS</th>
<th>BARRIER TYPE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1H</td>
<td>1</td>
<td>HYDROSTATIC PRESSURE</td>
<td>HORIZONTAL WELL, SHALLOW SURFACE &amp; TOC NOT ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C2H</td>
<td>2</td>
<td>PRODUCTION CASING + HYDROSTATIC PRESSURE</td>
<td>HORIZONTAL WELL, SHALLOW SURFACE &amp; TOC ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C3H</td>
<td>2</td>
<td>PRODUCTION CASING + CEMENT COLUMN</td>
<td>HORIZONTAL WELL, SHALLOW SURFACE &amp; TOC ABOVE SURFACE CASING SHOE</td>
</tr>
<tr>
<td>C4H</td>
<td>3</td>
<td>SURFACE CASING + CEMENT + HYDROSTATIC PRESSURE</td>
<td>HORIZONTAL WELL, DEEP SURFACE &amp; TOC NOT ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C5H</td>
<td>3</td>
<td>SURFACE CASING + CEMENT + PRODUCTION CASING</td>
<td>HORIZONTAL WELL, DEEP SURFACE &amp; TOC ABOVE TOP OF SUSSEX</td>
</tr>
<tr>
<td>C6H</td>
<td>4</td>
<td>2 CASING STRINGS + 2 CEMENT COLUMNS</td>
<td>HORIZONTAL WELL, DEEP SURFACE &amp; TOC ABOVE SURFACE CASING SHOE</td>
</tr>
</tbody>
</table>
### Category 1
- WELL COUNT: 399
- POSSIBLE BARRIER FAILURES: 92
- % FAILURE: 23.06%
- CATASTROPHIC BARRIER FAILURES: 3
- CATASTROPHIC FAILURE %: 0.75%
- AVG AGE OF WELL: 1986
- P&A WELL COUNT: 125
- CURRENT WELL COUNT: 114
- AVG SURFACE DEPTH (FT): 417
- AVG TOP OF CEMENT (FT): 7,296

### Category 2
- WELL COUNT: 7,811
- POSSIBLE BARRIER FAILURES: 276
- % FAILURE: 3.53%
- CATASTROPHIC BARRIER FAILURES: 6
- CATASTROPHIC FAILURE %: 0.08%
- AVG AGE OF WELL: 1994
- P&A WELL COUNT: 738
- CURRENT WELL COUNT: 5,446
- AVG SURFACE DEPTH (FT): 476
- AVG TOP OF CEMENT (FT): 6,022

### Category 3
- WELL COUNT: 3,407
- POSSIBLE BARRIER FAILURES: 20
- % FAILURE: 0.59%
- CATASTROPHIC BARRIER FAILURES: 1
- CATASTROPHIC FAILURE %: 0.03%
- AVG AGE OF WELL: 2007
- P&A WELL COUNT: 95
- CURRENT WELL COUNT: 4,548
- AVG SURFACE DEPTH (FT): 590
- AVG TOP OF CEMENT (FT): 2,719

### Total
- WELL COUNT: 16,828
- POSSIBLE BARRIER FAILURES: 401
- % FAILURE: 2.4%
- CATASTROPHIC BARRIER FAILURES: 10
- CATASTROPHIC FAILURE %: 0.06%
- AVG AGE OF WELL: 1,103
- P&A WELL COUNT: 15,725

### Category 1H
- WELL COUNT: 11
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2011
- P&A WELL COUNT: 0
- CURRENT WELL COUNT: 11
- AVG SURFACE DEPTH (FT): 613
- AVG TOP OF CEMENT (FT): 5,084

### Category 2H
- WELL COUNT: 132
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2012
- P&A WELL COUNT: 1
- CURRENT WELL COUNT: 131
- AVG SURFACE DEPTH (FT): 612
- AVG TOP OF CEMENT (FT): 2,003

### Category 3H
- WELL COUNT: 154
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2012
- P&A WELL COUNT: 2
- CURRENT WELL COUNT: 152
- AVG SURFACE DEPTH (FT): 669
- AVG TOP OF CEMENT (FT): 534

### Category 4H
- WELL COUNT: 9
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2011
- P&A WELL COUNT: 0
- CURRENT WELL COUNT: 9
- AVG SURFACE DEPTH (FT): 1,283
- AVG TOP OF CEMENT (FT): 5,608

### Category 5H
- WELL COUNT: 117
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2012
- P&A WELL COUNT: 0
- CURRENT WELL COUNT: 117
- AVG SURFACE DEPTH (FT): 1,005
- AVG TOP OF CEMENT (FT): 2,039

### Category 6H
- WELL COUNT: 550
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 0
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 2013
- P&A WELL COUNT: 0
- CURRENT WELL COUNT: 550
- AVG SURFACE DEPTH (FT): 1,002
- AVG TOP OF CEMENT (FT): 414

### Total
- WELL COUNT: 973
- POSSIBLE BARRIER FAILURES: 0
- % FAILURE: 0.00%
- CATASTROPHIC BARRIER FAILURES: 3
- CATASTROPHIC FAILURE %: 0.00%
- AVG AGE OF WELL: 970

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SPE-175401-MS • An Assessment of Risk of Migration to Fresh Water Aquifers: Fleckenstein
361 Existing Wells with Surface Casing Set Above the Base of the Fox Hills Aquifer
# Results After Determination of Aquifer Depth

Wattenberg Field, CO – New Assumption for Shallow Surface Casing Defined as Less than Base of Fox-Hills Aquifer or Adjacent Water Well Depth is Greater Oil and Gas Well Catastrophic Failure Summary

## Vertical Wells - (Shallow Casing is Assumed to Be Below Fox-Hills Contour or Offset Water Well Is Deeper Than Surface Casing)

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>WELL COUNT</th>
<th>POSSIBLE BARRIER FAILURES</th>
<th>% FAILURE</th>
<th>CATASTROPHIC BARRIER FAILURES</th>
<th>CATASTROPHIC FAILURE %</th>
<th>AVG AGE OF WELL</th>
<th>P&amp;A WELL COUNT</th>
<th>CURRENT WELL COUNT</th>
<th>AVG SURFACE DEPTH (FT)</th>
<th>AVG TOP OF CEMENT (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CATEGORY 1</td>
<td>166</td>
<td>100</td>
<td>60.24%</td>
<td>3</td>
<td>1.81%</td>
<td>1979</td>
<td>57</td>
<td>15</td>
<td>253</td>
<td>7,334</td>
</tr>
<tr>
<td>CATEGORY 2</td>
<td>621</td>
<td>219</td>
<td>35.27%</td>
<td>4</td>
<td>0.64%</td>
<td>1983</td>
<td>138</td>
<td>301</td>
<td>306</td>
<td>6,566</td>
</tr>
<tr>
<td>CATEGORY 3</td>
<td>45</td>
<td>15</td>
<td>33.33%</td>
<td>0</td>
<td>0.00%</td>
<td>1987</td>
<td>14</td>
<td>30</td>
<td>321</td>
<td>4,008</td>
</tr>
<tr>
<td>CATEGORY 4</td>
<td>7</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>1982</td>
<td>1</td>
<td>15</td>
<td>222</td>
<td>125</td>
</tr>
<tr>
<td>CATEGORY 5</td>
<td>8,789</td>
<td>77</td>
<td>0.88%</td>
<td>2</td>
<td>0.02%</td>
<td>1995</td>
<td>782</td>
<td>6,140</td>
<td>559</td>
<td>6,111</td>
</tr>
<tr>
<td>CATEGORY 6</td>
<td>5,434</td>
<td>7</td>
<td>0.13%</td>
<td>1</td>
<td>0.02%</td>
<td>2007</td>
<td>105</td>
<td>7,182</td>
<td>712</td>
<td>2,816</td>
</tr>
<tr>
<td>CATEGORY 7</td>
<td>1,766</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>2009</td>
<td>8</td>
<td>2,040</td>
<td>719</td>
<td>534</td>
</tr>
<tr>
<td>TOTAL</td>
<td>16,828</td>
<td>418</td>
<td>2.48%</td>
<td>10</td>
<td>0.06%</td>
<td>1,105</td>
<td>15,723</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Horizontal Wells - (Shallow Casing is Assumed to Be Below Fox-Hills Contour or Offset Water Well Is Deeper Than Surface Casing)

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>WELL COUNT</th>
<th>POSSIBLE BARRIER FAILURES</th>
<th>% FAILURE</th>
<th>CATASTROPHIC BARRIER FAILURES</th>
<th>CATASTROPHIC FAILURE %</th>
<th>AVG AGE OF WELL</th>
<th>P&amp;A WELL COUNT</th>
<th>CURRENT WELL COUNT</th>
<th>AVG SURFACE DEPTH (FT)</th>
<th>AVG TOP OF CEMENT (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CATEGORY 1</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CATEGORY 2</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CATEGORY 3</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CATEGORY 4</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CATEGORY 5</td>
<td>269</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>2012</td>
<td>1</td>
<td>268</td>
<td>789</td>
<td>2,153</td>
</tr>
<tr>
<td>CATEGORY 6</td>
<td>704</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>2012</td>
<td>2</td>
<td>702</td>
<td>929</td>
<td>442</td>
</tr>
<tr>
<td>CATEGORY 7</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>TOTAL</td>
<td>973</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>3</td>
<td>970</td>
<td></td>
<td></td>
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</tbody>
</table>
### Vertical Wellbore Categories

<table>
<thead>
<tr>
<th>BARRIERS</th>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
<th>RISK LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Shallow Surface Casing + Top of Production Casing Cement Below Over Pressured Hydrocarbon Reservoir</td>
<td>HIGH</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Shallow Surface Casing + Top of Production Casing Cement Below Under Pressured Hydrocarbon Reservoir</td>
<td>HIGH</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Shallow Surface Casing + Top of Production Casing Cement Above Top of Gas</td>
<td>LOW</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Shallow Surface Casing + Top of Production Casing Cement Above Surface Casing Shoe</td>
<td>LOW</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Deep Surface Casing + Top of Production Casing Cement Below Under Pressured Hydrocarbon Reservoir</td>
<td>LOW</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>Deep Surface Casing + Top of Production Casing Cement Above Top of Gas</td>
<td>LOW</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>Deep Surface Casing + Top of Production Casing Cement Above Surface Casing Shoe</td>
<td>LOW</td>
</tr>
</tbody>
</table>
### Horizontal Wellbore Categories

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Category</th>
<th>Description</th>
<th>Risk Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>SHALLOW SURFACE CASING + TOP OF PRODUCTION CASING CEMENT BELOW UNDER PRESSURED HYDROCARBON RESERVOIR</td>
<td>HIGH</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>SHALLOW SURFACE CASING + TOP OF PRODUCTION CASING CEMENT ABOVE TOP OF GAS</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>SHALLOW SURFACE CASING + TOP OF PRODUCTION CASING CEMENT ABOVE SURFACE CASING SHOE</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>DEEP SURFACE CASING + TOP OF PRODUCTION CASING CEMENT BELOW UNDER PRESSURED HYDROCARBON RESERVOIR</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>DEEP SURFACE CASING + TOP OF PRODUCTION CASING CEMENT ABOVE TOP OF GAS</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>DEEP SURFACE CASING + TOP OF PRODUCTION CASING CEMENT ABOVE SURFACE CASING SHOE</td>
<td>LOW</td>
</tr>
</tbody>
</table>
1. No evidence of aquifer contamination by stimulation operations through wellbores was discovered in the Wattenberg Field.

2. A total of 10 wells of the 17,948 wells in the study area exhibited signs of hydrocarbon migration to fresh water aquifers.

3. Migration of hydrocarbons into aquifers was found to primarily be associated with older wells, with surface casing which was not extended through aquifers.

4. The probability of hydrocarbon migration correlated to the age of the well. Older wells had less robust construction standards; and, the barriers preventing migration were not as redundant.
Conclusions

5. Probability of failure of one or more barriers in all vertical wells without hydrocarbon migration was determined to be 2.4%.

6. Probability of hydrocarbon migration due to one or more barrier failures in all vertical wells was determined to be 0.06%. Well constructed wells have a documented migration occurring in every 0.02% of the wells.

7. No evidence of failures of one or more barriers was detected in horizontal wells for shale development.

8. No evidence of hydrocarbon migration was found in horizontal wells used for shale development.
The authors acknowledge the support of the Colorado School of Mines Petroleum Engineering Department. We are also grateful for the efforts of Jan Mosnes - CSM, Troy Burke – University of Colorado-Boulder, and Stuart Ellsworth – COGCC, in support of this paper. This research is supported by the AirWaterGas Sustainability Research Network funded by the National Science Foundation under Grant No. CBET-1240584. Any opinion, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the United States National Science Foundation.
Thank You

Questions?