**Final grant report- Proposal for critical funding to sustain ExOIS**

**Nov. 1, 2024 – April 30, 2026 (includes 6 mo. no cost extension)**

**$882,836 from OV plus WHOI cost-share on overhead (total WHOI CS $315,921).**

This report covers a period of approximately 18 months of activities related to the Program Office of Exploring Ocean Iron Solutions (ExOIS), an international consortium of over 65 team members and 35 institutions housed at the Woods Hole Oceanographic Institution. ExOIS focuses on defining and executing a research agenda for ocean iron fertilization (OIF) to answer critical questions about its potential efficiency for atmospheric carbon dioxide ($CO_2$) removal, as well as its ecological and environmental impacts (http://oceaniron.org).

During this project period, ExOIS used this support to build and coordinate a major international consortium, advance governance and permitting readiness, and generate significant scientific momentum and community output, including regarding the design of field trials. ExOIS also supported modeling intercomparisons, which are key for understanding uncertainties in existing models, and for field planning and extrapolating OIF impacts to larger regional and climate relevant scales. Taken together, we have advanced the scientific and public understanding of OIF. Importantly, this progress also advances the priorities of the larger mCDR (marine carbon dioxide removal) community.

Note for the purposes of this report, we highlight activities that were largely funded by a grant administered by Ocean Visions, but some of these activities were supported by a combination of funding sources including from WHOI and other private Foundations.

**Summary of key deliverables over the grant period**

- 25+ presentations by 13 ExOIS team members helped establish ExOIS as a leader in emerging OIF and mCDR fields
- 4 written reports and peer reviewed papers on mCDR and OIF motivation, science, governance, and social science issues involved scores of experts to summarize key state of the knowledge
- 2 modeling intercomparison manuscripts (in preparation) document how model diversity allows for the leveraging of an ensemble approach to address model uncertainties
- 15 community forums hosted allowed us to engage with 100's of different mCDR practitioners, funders, policy makers and communications experts
- Significant contributions to the PCS report and written feedback provided on 2 other mCDR permits, a carbon credit methodology, and a congressional mCDR bill made tangible differences in these efforts
- Permit pre-application initiated and submitted to the EPA as the first step to becoming the first high seas mCDR filed permit
- Ongoing interactions and central contact for OIF with other mCDR groups/activities, which contributed to the building out and development of the emerging mCDR community
- Coordination of a 60+ person (and growing) consortium of experts across OIF and mCDR research, governance, and social science, providing a wide range of perspectives from different geographic, expertise, and career stage perspectives.

**For the remainder of this report, we break down our efforts into the three main activities:**

**1) the ExOIS Program Office;**
**2) pre-application groundwork for field permits; and**
**3) advancing a modeling intercomparison study.**

**1) Program Office**

The **ExOIS Program Office** (PO) serves to gather and advance the collective ideas of ExOIS members and the larger OIF community. Currently the PO staffing includes Paul Morris (FT), Ken Buesseler, Katie Roche, and Jessica Drysdale (all PT under this funding). The PO works with ExOIS members and with the guidance from a 5 person Steering Committee (S. Smith- MLML, M. Wells- U. Maine, J-E Yoon- Korea Polar Inst, F. Chai- U. Xiamen, K. Ramakrishina- WHOI). The ExOIS Program Office manages the resources required to accomplish the goals of ExOIS and initiates and organizes group forums, coordinates workshops, hosts regular meetings of the ExOIS Steering Committee (SC), facilitates contacts among participants, seeks out and interacts with potential sponsors, and engages with the wider community. The Program Office organized and facilitated specifically the creation of reports, whitepapers, and other content (on international governance; social science; and field trials); organized attendance and representation of ExOIS at appropriate national and international conferences and smaller meetings; and importantly during this project period, coordinated and provided input to the Phytoplankton Carbon Solutions (PCS) program at Ocean Visions.

**Deliverables**

During this project period, as supported by this grant and contributions from other sources, specific milestones and deliverables, grouped by activity, included:

**OIF community building & broader engagement with the wider mCDR community**

a. ExOIS forums: ExOIS hosted monthly Zoom forums with invited speakers to encourage scientific discussion of research priorities, methodologies, governance issues, and public policy surrounding OIF. A full list of forum speakers, themes, and topics can be found on the ExOIS website (https://oceaniron.org/our-plan/). During this project period, forum speakers/topics included:
    i. Modeling intercomparison (D. McGillicuddy)
    ii. OIF in LNLC settings (S. John & E. Seleen)
    iii. Multiple presentations on the PCS report (E. Schwab)
    iv. Gigablue (S. Markus-Alford)
    v. Air-Sea $CO_2$ exchange (B. Ward)
    vi. Social Science working group report (L. Bastian & A. Murthy)
    vii. mCDR and OIF impacts on oxygen (A. Oschlies & K. Buesseler)
    viii. Highlights NYC Ocean Climate week (P. Morris)
    ix. Engagement with Pacific NW communities (B. Warren, W. Burns & G. Belotti)
    x. Update on Phytoplankton Carbon Solutions (E. Schwab & L. Kapsenberg)

xi. Industry perspective on funding (A. Alferness), Fe from produced water (J. Alexander)
xii. International governance and permitting of mCDR projects (A. Murthy & K. Roche)

b. Organized mCDR talks and posters in December 2025 in DC as part of fall AGU. This included hosting a social event at Artechouse to gather the mCDR community.
c. Working with OV on PCS landscape review. This was a significant activity, with KB and PM meeting ≈2x per month with Eric Schwab and Lydia Kaspenberg, providing input on PCS activities, passing on background materials and leads to individuals and groups active in the PCS landscape, and feedback on draft concepts & reports.
d. Written feedback on mCDR issues was also provided on: OIF registries- PURO public review of GigaBlue protocols; EPA permits- comments on LOCNESS and Carboniferous plans; Congressional bills- feedback and meetings with congressional staff on the bipartisan Ocean ReSCUE Act (Offices of Schatz, Murkowski, Carter and Bonamici)
e. Interactions w/other mCDR groups, including: CtoSea, EIAF Fugro, C180, eNGO's, ASU, Puro, Gigablue, and others

**Participation and organization of presentations and panels at public events**

a. COP29 panels in Baku, Azerbaijan, Nov 2024 (Paul Morris, Kilaparti Ramakrishna)
b. Geography 2050 panel in New York City, Nov 2024 (Ken Buesseler)
c. PICES conference ExOIS event, Honolulu, Nov 2024 (Mark Wells, Fei Chai)
d. AGU poster and talk, Washington DC, Dec 2024 (Ken Buesseler, Paul Morris, Jessica Drysdale)
e. Xiamen Symposium on Marine Environmental Sciences, Xiamen, China, Jan 2025 (Fei Chai, Mark Wells)
f. WHOI Marine WHOI Marine Chemistry & Geochemistry seminar, Feb 2025 (Ken Buesseler, Paul Morris, Dennis McGillicuddy, Kilaparti Ramakrishna)
g. Ocean Visions Summit, Vancouver, Canada, Mar 2025 (Ken Buesseler, Paul Morris, Kilaparti Ramakrishna, Jay Cullen, Brad Warren)
h. NOAA PMEL Symposium Series invited talk, Seattle, Mar 2025 (Ken Buesseler)
i. EarthX panel, Dallas, Apr 2025 (Paul Morris, Seth John)
j. International Liège Colloquium on Ocean Dynamics talk and poster, Liège, Belgium, May 2025 (Mark Wells, Sarah Smith)
k. One Ocean Science Congress poster, Nice, France, Jun 2025 (Paul Morris, Sarah Smith, Fei Chai, Kilaparti Ramakrishna)
l. UN Ocean Decade Conference hosted panel, Nice, France, Jun 2025 (Paul Morris, Kilaparti Ramakrishna, Sarah Smith)
m. Global Ocean Oxygen network (IOC-UNESCO expert working group, $GO_2NE$) webinar, July 2025 (Ken Buesseler & Andreas Oschlies)
n. Climate Week NYC panel, New York City, Sep 2025 (Ken Buesseler, Paul Morris, Katherine Roche)

o. COP30 panels in Belém, Brazil, Nov 2025 (Ken Buesseler, Kilaparti Ramakrishna, Margaret Leinen)
p. Nature Tech Collective webinar, Dec. 2025 (Ken Buesseler)
q. Line P Workshop invited talk, Vancouver, Canada, Feb 2026 (Ken Buesseler)
r. OSM posters, town hall, and reception Feb 2026 (Ken Buesseler, Paul Morris, Katherine Roche) and presentation regarding modeling intercomparison (Dennis McGillicuddy) & more on this below

**General public engagement**

a. ExOIS website: oceaniron.org
b. Social media channels:
    i. Blue Sky: https://bsky.app/profile/exois-oceaniron.bsky.social
    ii. LinkedIn: https://www.linkedin.com/company/exploring-ocean-iron-solutions-exois
    iii. X (Twitter): https://x.com/ExOIS_OceanIron (discontinued but remains accessible)
    iv. YouTube: https://www.youtube.com/@ExOIS_OceanIron
c. Some examples of engagement with media from local to international levels:
    i. Aventine article interview with Ken Buesseler, Nov 2024
    ii. My Science Blast podcast with Sarah Smith, Jan 2025
    iii. Grist article with Sarah Smith, Aug 2025
    iv. Alaska Beacon news commentary with Ken Buesseler, Nov 2025
    v. Liquid Trees podcast with Mark Wells, Dec 2025
    vi. WHOI press release with Ken Buesseler, Margaret Leinen, Brad Warren, Feb 2026

**Preparation of publications and reports (peer reviewed when indicated)**

a. Exploring Ocean Iron as a Potential Climate Solution. Public facing information brochure, written by PO staff w/ support from K. Kostel and other WHOI staff for layout (April, 2025).

b. Buesseler K.O., Bianchi D., Burns W., Chai F., Cullen J.T., Estapa M., Honda M., John S., Karl D.M., Klaas C., Li D., Liu Z., McGillicuddy D.J., Morris P.J., Nishioka J., Omand M.M., Ramakrishna K., Roche K.M., Siegel D.A., Smith S.R., Twining B.S., Wells M., White A., Xiu P. and Yoon J-E. (2026) The Case for Ocean Iron Fertilization Field Trials. *Dialogues on Climate Change, 0(0). Peer reviewed*. https://doi.org/10.1177/29768659261420631

c. Bastian, L., Nawaz, S., Webb, R., Bellamy, R., Borth, A., Hilser, H., McDonald, J., Proelss, A., Wade, E. & Weir, M. (2025). *Guiding Recommendations on Collaborative Research Governance, Community Engagement, and Social Science for the 'Exploring Ocean Iron Solutions'(ExOIS) Project Office: A Focus on the First 12 months of Field Trial Planning Prepared by the ExOIS Social Science and Governance Advisory Board*. Exploring Ocean Iron Solutions. Available at: https://oceaniron.org/our-plan/

**2) Pre-application for field permit**

The pre-application activities not only lay the groundwork for obtaining an EPA permit for OIF fieldwork, but they also encompass critical international governance and community engagement efforts that advance the entire field of mCDR. During the grant period, ExOIS developed an EPA permit pre-application that justifies the need for OIF field research, details the research and monitoring plans, and considers potential environmental impacts and mitigation approaches. This pre-application received input from 28+ researchers at 20+ institutions. Since fieldwork will take place in international waters, a team of governance experts developed an open-access report analyzing the London Convention/London Protocol (LC/LP) assessment framework for OIF mCDR research and provided an evaluation of ExOIS's research plans in the context of these international laws. This report will be valuable for mCDR research projects beyond the ExOIS field trials, as to date there has yet to be an mCDR research project in international waters under the LC/LP.

In addition to domestic and international governance, a key aspect of mCDR research is co-design and engagement with interested and impacted communities. To ensure that community interests are represented in the experimental design, we are actively engaging with scientists, members of the commercial fishing industry, and Indigenous leaders in Alaska, the U.S. Pacific Northwest, and Canada. We prioritize early, ongoing, and transparent dialogue to understand concerns, share information, and incorporate relevant perspectives. Engagement activities include educational briefings, listening sessions, working groups, and other opportunities for two-way communication.

**Deliverables**

During this project period, as supported by this grant and contributions from other sources, specific milestones and deliverables, grouped by activity, included:

**Development and submission of EPA permit pre-application**

a. Onboarding of Katie Roche (early career researcher) to the ExOIS Program Office
b. Multiple online and one in-person meeting with the EPA mCDR permitting team
c. Convening of an iron deployment working group consisting of 10 members (8 institutions, 6 countries) to develop the iron and tracer release plan
d. Meetings with NOAA Fisheries and other agencies/experts in environmental impacts of mCDR
e. Preparation of a draft permit pre-application with input from the ExOIS Steering Committee and 28-person research team. Pre-application submitted to the EPA in Feb 2026.

**International governance of OIF report**

a. Subcontract to Romany Webb at the Columbia Law School Sabin Center for Climate Change Law to prepare a report on international governance of OIF research, including ensuring field research follows the LC/LP for material release in international waters.
b. Resulting open-access report: Murthy, A., & Webb, R. (2026). *International Governance of Ocean Iron Fertilization Research: A Case Study of the Proposed Exploring Ocean Iron*

*Solutions Field Experiments*. Sabin Center for Climate Change Law. https://scholarship.law.columbia.edu/sabin_climate_change/268

**Regional community engagement**

a. Co-design and feedback from interested communities is essential for the success and societal acceptance of mCDR research. Over the grant period, ExOIS has developed relationships and communicated with various groups in Alaska, the U.S. Pacific Northwest, and Canada to advance community engagement:
    i. Global Ocean Health – Seattle, WA, USA
    ii. Fishery Friendly Climate Action Campaign, AK & RI, USA
    iii. Community Leaders and mCDR Project – Anchorage, AK, USA
    iv. An Alaska based mCDR journal club – AK, USA
    v. University of Alaska Fairbanks – Fairbanks, AK, USA
    vi. University of Victoria – Victoria, BC, Canada
    vii. Alaska Ocean Observing System – Anchorage, AK, USA

b. Presentations at regional conferences, aimed at engaging scientists, members of the commercial fishing industry, and Indigenous groups:
    i. Alaska Marine Science Symposium, Anchorage, AK, Jan 2025 (Mark Wells, Brad Warren)
    ii. Western Alaska Interdisciplinary Science Conference, Bethel, AK, April 2026 (Mark Wells, Brad Warren)
    iii. ComFish Expo, Kodiak, AK, April 2026 (Brad Warren, Katie Roche)

c. Ongoing engagement in collaboration with Global Ocean Health
    i. Participation in monthly meetings with the Working Group on Management of Marine Carbon Removal with commercial fishermen and Indigenous leaders (monthly since Jan 2026)
    ii. Representation of ExOIS at fisheries management council meetings in Alaska and the Pacific NW

**3) Modeling intercomparison study**

Detailed simulations of the proposed field trials have been implemented using several different state-of-the-art models run at high resolution. Presently, three regional coupled physical-biogeochemical models from Woods Hole Oceanographic Institution (MOM6-COBALT version 2.0), University of California Los Angeles (ROMS-/BEC), and Xiamen University/University of Maine (ROMS-CoSINE) have been run with a set of common numerical protocols. An example snapshot 20 days after iron release (Figure 1) reveals transport and stretching of the fertilized patch, as well as the drawdown of nitrate, accumulation of large phytoplankton, and export to the deep ocean. Note that the response to fertilization is couched within a complex turbulent background, which complicates assessment of the response via differencing between inside and outside the patch—as both contain spatial heterogeneity. The observational requirements for so doing will be assessed in the next phase of the work with observing system simulation experiments (OSSEs).

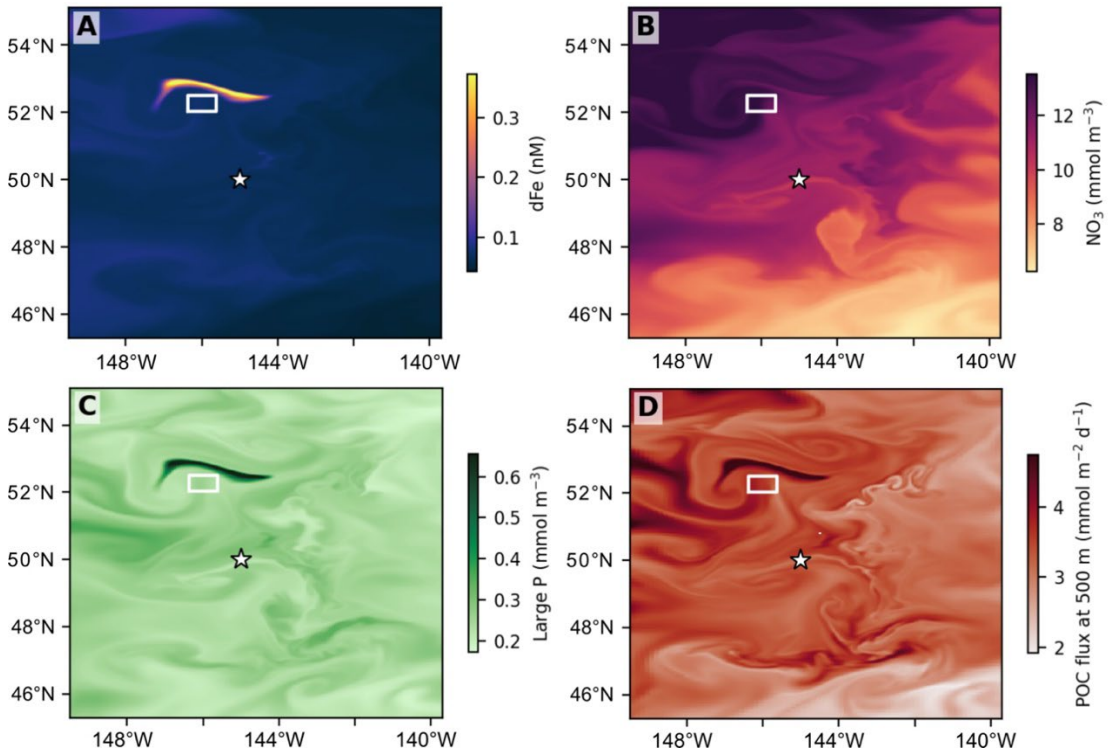


**Figure 1. Snapshots from MOM6-COBALT 20 days after iron release within the white box: [A] surface dissolved iron, [B] surface nitrate, [C] surface large phytoplankton abundance, and [D] particulate organic carbon flux at 500 m. The star represents Ocean Station Papa.**

Simulated responses of the three models have been compared to observations from the SERIES experiment was conducted near Station P in 2002 (Figure 2). There are several reasons why differences between the predictions and the observations are to be expected. First, forcing for the simulations comes from 2010 rather than the year of the experiment, and in any case the mesoscale and submesoscale turbulence cannot be simulated deterministically in these non-data-assimilative models. Second, the observed response is computed from the differences between single stations inside and outside the patch and thus does not account for heterogeneity in either. Specifically, the peak inside the patch may not have been captured, and the chosen location outside the patch could be either above or below mean background conditions. This superimposes unknown uncertainty in the "inside – outside" estimates. In contrast, the three-dimensional model results are known with certainty, and thus the magnitude of the response can be computed directly from differences between the experiment and control simulations. Lastly, models are of course approximations of the natural system, and therefore cannot be expected to match the observations without error. This is a primary motivation of this intercomparison, insofar as all of the models are *a priori* equally plausible representations of the ocean.

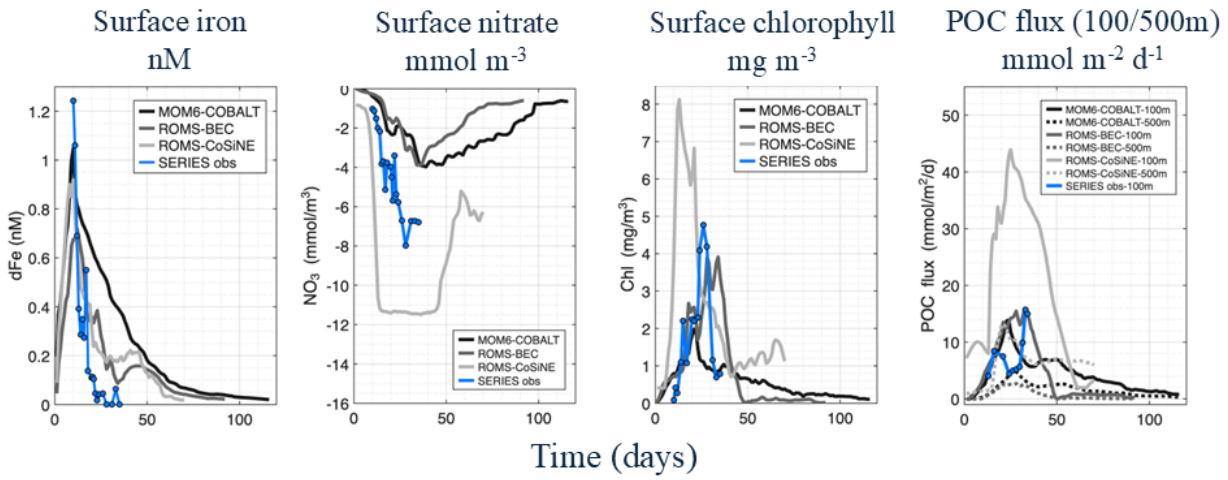


**Figure 2. Comparison of SERIES observations (inside – outside the patch) with model results (positive [in the cases of dFe, Chl, and POC flux] or negative [in the case of $NO_3$] extrema in the differences between experimental and control simulations).**

Results indicate that the models generally bracket the observations (Figure 2). In the case of dFe, the models underestimate the concentration early in the experiment, and overestimate it later in the experiment, with simulated perturbations in dFe persisting tens of days after the SERIES patch was drawn down to undetectable levels. The models predict a wide spread of nitrate utilization, ranging from complete drawdown in ROMS-CoSINE to more modest uptake in ROMS-BEC and MOM6-COBALT. These differences are attributed to efficient aggregation and export of diatoms in ROMS-CoSINE, whereas top-down control in ROMS-BEC and MOM6-COBALT prevents full utilization of nitrate. As expected, chlorophyll accumulation and POC export are highest for ROMS-CoSINE and lower in the other two models. Again, there are differences in timing and magnitude, but the observations generally fall within the range of the simulated values. This lends confidence to our *a priori* assumption that all of the models are plausible representations of reality, and thus we plan to proceed to seek new support for OSSEs based on these and any other models we can entrain that meet these criteria. In doing so, we will leverage an ensemble approach to benefit from model diversity and account for model uncertainty

**Summary of funding**

The subtotal for the PO activities support was approximately $495K ($331K from OV; $163K WHOI cost share), plus additional funds from WHOI and other sources. This funded roughly 2 FTE's split mostly between P. Morris, K. Buesseler, and J. Drysdale during the project period. Other costs were related to travel, conference fees/venue rentals, web and computer services, production of written materials and handouts/printing, honoraria for SC members ($3K each except KR).

The subtotal for the pre-application groundwork was approximately $206K ($149K from OV; $57K WHOI cost share), with additional funding by the McConnell Family Foundation. This component funded partial salary of K. Roche as well as 0.5 mo. for K. Ramakrishna and included a subcontract to Sabin Center at Columbia University ($50K) for the production of their report on international governance of OIF field studies.

The subtotal for modeling work as approximately $497K ($402K from OV; $95K WHOI cost share), with additional in-kind support (salaries) by participating modeling groups. This funded D. McGillicuddy to lead intercomparison between his modeling team and two others at UCLA and Xiamen, both supported by subcontracts here (D. Bianchi/$130K and F. Chai/$75K, respectively). M. Long at C-Worthy had an advisory role ($30K subcontract). Funding was used for salaries of PI's and their teams related to modeling as described in this report, including two postdoctoral researchers. Results from this modeling effort were used in the EPA permit pre-application and will be published in multiple peer-reviewed manuscripts.

A full WHOI accounting of spending is being prepared separately.

**What comes next?**

The ExOIS Program Office will be seeking to build upon the foundation laid out in this report. We have built up trust within the mCDR community and with public audiences. The next few years are critical as we make the scientific and public case for OIF and mCDR. Ultimately, this work will require the highest quality field studies in several settings, but also the path ahead will also require improvements in models, particularly as they relate to biological impacts; improving MRV and eMRV technologies for monitoring C and ecological impacts; supporting social science and governance experts for the responsible and equitable advancement of mCDR; and specific to OIF, improving delivery and bioavailability of iron. Arguably, without ExOIS, the responsible consideration of OIF would not be advancing at a time when commercialization of mCDR is happening faster than the research to support it. We have learned from OIF in decades past, that in a vacuum without legitimate scientific attention and research, bad behavior by rouge actors will hurt not just OIF, but all forms of mCDR and result in a loss of public trust, making good ideas and intentions even harder to consider, and much less acceptable to implement. A thriving and open academic based consortium such as ExOIS is essential to the future of mCDR.