Does EUI Fully Capture the Carbon Footprint of a VRF System? Using a Life Cycle Approach to Assess VRF System Emissions

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Variable refrigerant flow systems are a popular technology for heating and cooling buildings due to their energy efficiency. VRF systems run on electricity, with no onsite fossil fuel combustion, which makes them attractive in the context of GHG emissions reductions through building electrification and grid decarbonization. Traditionally, the environmental performance of HVAC systems has been measured using the energy use intensity metric. This study aims to assess whether EUI adequately captures the GHG emissions associated with the life cycle of the VRF system.

While life cycle assessments have been performed on HVAC systems, this is the first known cradle-to-grave LCA of a VRF system. The study aims to quantify GHG emissions for a VRF system in use at a LEED certified office building in Seattle, WA. The LCA examines carbon impacts in three key categories: the materials required for system assembly, operational electricity, and refrigerant use. Results show that electricity use represents 47% of the carbon footprint and refrigerant use represents 52%. System materials are a less significant contributor to carbon footprint, at 1% of the total.

The results suggest that energy use intensity is not a sufficient metric to quantify the carbon footprint of VRF systems and that a greater focus on refrigerant management is needed. Building designers should design VRF systems with a focus on optimized energy efficiency and low-impact refrigerant strategies, and not on equipment quantity, in order to minimize the carbon footprint of VRF systems over their lifetimes.

INTRODUCTION

Variable refrigerant flow (VRF) systems are becoming an increasingly popular technology for heating and cooling of residential and commercial buildings due to their energy efficiency. A VRF system conditions a building by circulating hot or cold refrigerant throughout conditioned zones at variable flow rates to meet individual space demands. The system consists of an outdoor unit (or multiple units) within which the vapor compression cycle operates to heat or cool the heat transfer fluid, refrigerant. The refrigerant is then circulated throughout the interior of the building via piping to in-zone terminal units, which in turn blow air over refrigerant coils to heat or cool the space. Refrigerant distribution throughout the building is controlled by a system of branch controllers within the piping system, in between the outdoor units and indoor units.

VRF systems can decrease site heating, ventilation and air conditioning (HVAC) energy use by 15-42% as compared to conventional rooftop variable air volume (VAV) systems in the United States (Kim, et al. 2017). The demand by building owners for VRF systems is increasing (Turpin 2017, Murphy 2014), and this can be attributed in part to building energy codes across the United States continuing to raise efficiency standards for HVAC systems. While energy modeling for HVAC systems is an established practice in industry and academia, there is a lack of studies available that deal with the life cycle carbon footprint of system equipment and operation.

This study aims to understand whether energy use intensity (EUI), a common metric for quantifying the energy use and associated environmental impacts of an HVAC system, is sufficient to capture the carbon footprint of a VRF system. EUI focuses exclusively on system energy use, however the system is made of high-embodied carbon materials such as metals and operates using high global warming potential (GWP) refrigerants. Is use of EUI as a metric for building decarbonization leaving significant greenhouse gas (GHG) emissions out of the picture?

LITERATURE REVIEW

There has been an effort in recent years to apply LCA methodology to HVAC systems, but no studies were identified in the literature review that specifically focused on VRF systems. One study focuses on a residential apartment in China and compares life cycle GHG emissions of two heating systems—a decentralized hot water radiator and distributed heat pump system. The study breaks the cradle-to grave-life cycle inventory into three groups consisting of raw material supply, operational requirements and recycling and disposal at end-of-life (Zheng, Fang and Yu 2016). Another study calculates cradle-to-grave environmental impacts of residential air conditioning in Saudi Arabia (Almutairi, et al. 2015). There are several studies in the literature that perform life cycle cost analyses on different types of HVAC systems (Song, Lu and

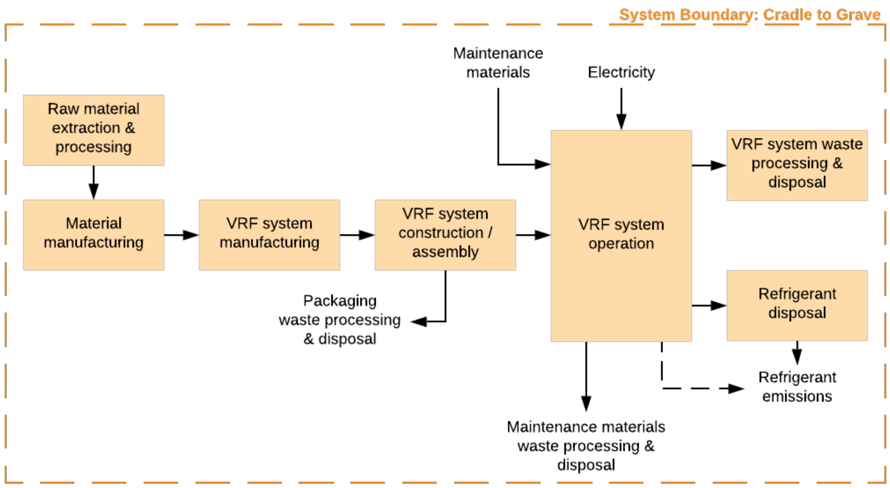

Figure 1. LCA system boundary, cradle to grave.

Ma 2017). Some of these studies compare energy use of VRF systems to more mature technologies such as VAV (Kim, et al. 2017, Yu, et al. 2016).

LCA methodology has also been applied to refrigerants used in HVAC and refrigeration systems. Two of the studies reviewed compare the carbon footprints of a range of refrigerants in room air conditioning (Zhao, Zeng and Yuan 2015) and supermarket refrigeration systems (Bovea, Cabello and Querol 2007) while a third quantifies human health risks from production and emissions of various refrigerant types (Xue, et al. 2019).

GOAL AND SCOPE OF THE STUDY

The goal of this study is to quantify the GHG emissions associated with the manufacture, installation, operation and end-of-life of a VRF system in a commercial building located in Seattle, Washington. The results of this study are intended to inform the architecture, engineering and construction community of the hotspots for GHG emissions in VRF systems. The results of this study will compare relative impacts of embodied carbon in equipment, emissions from refrigerant use, and energy-related emissions during operation to help focus on areas of HVAC systems that have potential for meaningful GHG emissions reductions. This study also aims to determine whether EUI is a sufficient metric for assessing the carbon footprint ofa VRF system.

FUNCTIONAL UNIT

The function of the system is to provide heating and cooling to a commercial building to meet thermal comfort requirements as determined by the local building code. The functional unit for this study is one (1) complete VRF system that provides heating and cooling to a commercial building for approximately 3500 hours annually for 15 years (Schoen 2010). As VRF systems typically decouple space conditioning from ventilation, ventionation is excluded from the functional unit and no equipment for ventilation is included in this study.

SYSTEM BOUNDARIES

This study is cradle-to-grave in scope. Figure 1 outlines the scope and boundary of the LCA. There is a focus on GHG emissions from equipment manufacturing, operational energy use and refrigerant emissions.

GEOGRAPHIC COVERAGE

This LCA is focused on a commercial office building located in Seattle, Washington. All equipment included in the study is commercially available in North America. Background data for the LCA is representative of the country- and region-specific situation, with European proxies used where US background data was unavailable.

TEMPORAL COVERAGE

The VRF system under study was installed in 2014, with its first year of operation in 2015. As such, the reference year for this study is 2015. Background data for the LCA is representative of the years 2007-2019.

CUTOFF CRITERIA

The VRF system was modeled using best available LCI data for the various components of the system. A 1% mass cutoff was applied to all mechanical equipment, i.e. all materials that make up less than 1% of the mass of the system were excluded from the study.

SOFTWARE AND DATABASE

The LCA model was created using the GaBi software for life cycle engineering, developed by Sphera Solutions, Inc. The GaBi Education 2018 database (Sphera Solutions, Inc. 2018) provides the life cycle inventory data for the background system.

SELECTION OF LCIA METHODOLOGY

The building sector is a major contributor to GHG emissions and climate change in the United States, with residential and commercial buildings accounting for 34% of domestic GHG emissions (Desai and Camobreco 2020). As such, this study focuses on the VRF system's contribution to climate change. GHG impacts and contribution to climate change are assessed based on the United Nations Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013) global warming potentials (GWPs), excluding biogenic carbon.

LIFE CYCLE INVENTORY

The reference flows the make up the foreground system consist of materials that make up the VRF equipment and operational flows for the system such as energy and refrigerant. The indoor units, outdoor units and branch controllers are made up of metal, plastic and packaging materials. Operation of the system requires electricity, refrigerant and maintenance materials. Figure 2 (a) lists reference flows for the system.

MECHANICAL EQUIPMENT

The outdoor condensing units, branch controllers and indoor terminal units are composed of metals and plastic, with wood and cardboard packaging. Unit quantities, capacities and model numbers were taken from construction drawings for the building. Total shipped weight for each unit was determined from Mitsubishi catalogue data, and material breakdowns for the units were estimated using percentages from an EPD for VRF outdoor condensing units developed by Uniclima for PEP Ecopassport, a French environmental reporting program for HVAC and electrical products (Uniclima 2018).

Based on a review of Mitsubishi service manuals, the components within outdoor and indoor units and branch controllers were deemed similar enough to assume that the material breakdown for the three unit types can be represented by the Uniclima EPD. The unit types feature copper piping, steel housing, printed wiring board controllers, and miscellaneous plastic and metal fasteners and spacers. The indoor and outdoor units also include aluminum fans and polypropylene fabric filters. The units ship with cardboard and wood packaging which is disposed of as part of the VRF system construction process. A cutoff was applied to the Uniclima EPD so that no materials that make up less than 1% of the unit mass were included. Refrigerant was also not included in the weight of the equipment and is accounted for separately. The materials that were modeled represent 94% of the total mass of the equipment.

Refrigerant is distributed between the equipment components throughout the building via copper piping. This piping is insulated with closed-cell foam with thickness established by the local building code. Pipe quantities were determined using Mitsubishi's system layout and selection tool, Diamond System Builder (DSB).

TRANSPORTATION

Mitsubishi manufactures equipment and components for its VRF systems in Wakayama, Japan and distributes products to the west coast of the United States via a warehouse in Mira Loma, California. Transportation from Japan to California is via barge and transportation to the project site from California is via diesel truck. Waste is hauled to Arlington, Oregon from the project site via diesel truck at the system end-of-life. Transportation of refrigerant and equipment maintenance materials are not considered within the scope of this study.

(a)

Reference flow	Unit	Value	Reference flow	Unit	Value
Equipment			**Operation**		
Aluminum	kg	324	Electricity	kWh	4,042,710
Copper	kg	2,196	PP filters	kg	2,919
PP	kg	154	R410A input	kg	531
PWB	kg	77	R410A emissions	kg	165
Steel	kg	3,314	**End of Life**		
Packaging			Mixed plastics	kg	424
Cardboard	kg	123	Corrugated containers	kg	123
PE	kg	270	Dimensional lumber	kg	755
Wood	kg	755	Mixed metals	kg	6427
Piping			Mixed C&D waste	kg	234
Copper	kg	593	R410A emissions	kg	14
Closed-cell insulation	kg	157			

(b)

Parameter	Unit	Value
Building Area	ft^2	45,169
Building EUI	$kBtu/ft^2$	37.2
Total Electricity	kWh	467,104
Total Natural Gas	therms	851
Space Heating Electricity	kWh	20,998
Space Cooling Electricity	kWh	43,862
Ventilation Fans Electricity	kWh	10,002
Total Mechanical System Electricity	kWh	74,865
Mechanical System Energy as % of Total	%	15.2%

Figure 2. (a) Reference flows for VRF system manufacturing, operation and end of life. (b) Energy consumption profile for the building, modeled in EnergyPro software.

OPERATION AND MAINTENANCE

The requirements for operation of the VRF system fall under three main categories – electricity, refrigerant, and maintenance. The system requires electricity to power the vapor compression cycle and circulates refrigerant to provide heating and cooling to the building. Electricity use for the system was estimated using results from an energy model built using EnergyPro software in 2012 for the building as part of its LEED certification. Figure 2 (b) summarizes energy consumption and modeling results for the whole building and HVAC system.

The heat transfer fluid for the system is R410A refrigerant, which is a blend of difluoromethane and pentafluoroethane. It is a hydrofluorocarbon (HFC) with no ozone depletion potential and a high GWP relative to carbon dioxide. The amount of refrigerant required for system operation was estimated using DSB. The VRF system was initially charged with 366 kg of R410A during start-up and is topped up over the system lifetime as refrigerant leaks out of the system during normal operation and maintenance activities. The refrigerant leak rate was determined based on the system type to be 3.0% annually (Thomas and Munoz 2017). This results in emissions and recharge of 165 kg of refrigerant over the system lifetime of 15 years.

Routine maintenance for the system consists of replacement of indoor air filters four (4) times annually. Maintenance logs

Life Cycle Stage	Manufacturing	Construction	Operation	End of Life
GWP (kg CO_2eq.)	1.73E+04	7.19E+03	6.76E+05	4.64E+04

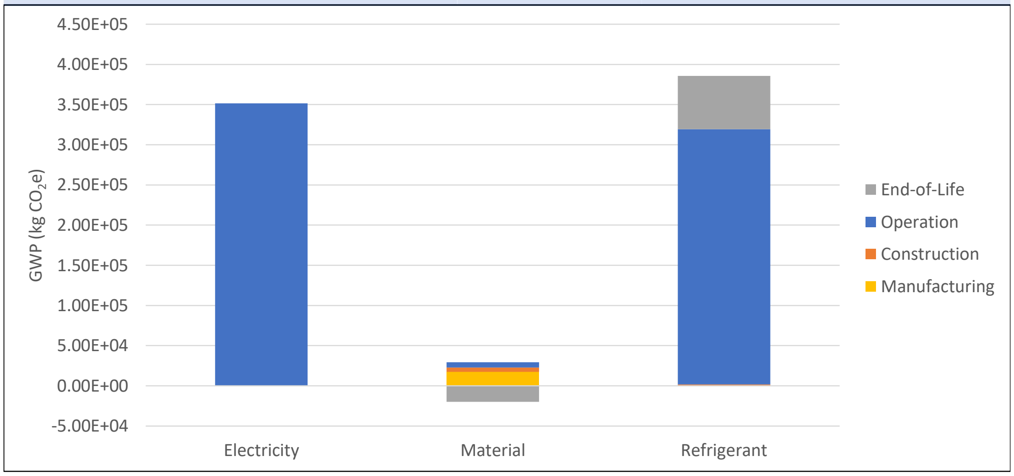

Figure 3. Cradle to grave results by life cycle stage and system component.

for the building for the past three (3) years of operation were reviewed and did not reveal any significant maintenance activities beyond regularly scheduled service, therefore the assumption was made that the only materials required for maintenance are polypropylene fabric air filters.

END-OF-LIFE

The disposal of packaging during construction and system materials at end-of-life was modeled as an open-loop recycling and disposal system. End-of-life GHG impacts were calculated by inputting local recycling and landfill rates for various material streams into EPA's Waste Reduction Model (WARM). 64% of commercial waste is recycled in Seattle and the remainder is landfilled (Seattle Public Utilities 2018).

Refrigerant is recovered from the VRF system at deconstruction and transported offsite for end-of-life processing. Leakage rates of 1.8% during system evacuation and 2.0% during end-of-life transportation and storage were utilized (ICF International 2018). R410A is filtered and reclaimed or destroyed via incineration after recovery from the system. Reclamation and destruction rates of 80% and 20% respectively were used per data from the California Air Resource Board's Refrigerant Management Program. The reclamation process is assumed to have negligible environmental impact. The incineration process was modeled using the National Aeronautics and Space Administration's Chemical Equilibrium with Applications (NASA CEA) program to determine combustion products.

LIFE CYCLE IMPACT ASSESSMENT RESULTS

The LCA results for the VRF system are presented in Figure 3, broken down by life cycle stage. It can be seen that electricity and refrigerant are the most significant contributors to the life cycle carbon footprint of the system, accounting for 47% and 52% respectively. For refrigerant, the majority of the impact is due to leaked emissions during system operation, however emissions at end-of-life are also a contributor. The embodied burden of mechanical equipment materials has a small 1% contribution to the system's carbon footprint, which is partially offset by the recycling of metals at end-of-life.

SENSITIVITY ANALYSIS

Operational energy use for the system was based on energy model results in the absence of actual electricity consumption data for the building. Modeled energy use has limited applicability to actual building operations, which can vary year over year based on occupant needs and weather conditions (Frankel and Turner 2008). To assess the effects of variations in electricity consumption on the system carbon footprint, the annual electricity use of the VRF system was varied from 50% to 200% of the base case 74,865 kWh annually. The results of the sensitivity analysis demonstrate that for every 10% change in system energy use, the carbon footprint of the system shifts by 5%. This is illustrated in Figure 4.

SCENARIO ANALYSIS

Two scenario analyses were developed to gain an understanding of potential pathways for decarbonization of the VRF system. The first scenario analysis considered the impacts of use of lower-GWP refrigerant alternatives, while the second considered the effect of installing the system in different regions.

DROP-IN REFRIGERANT ALTERNATIVES

At the time of writing, R410A is widely accepted as the standard refrigerant for use in VRF systems. It has a high GWP and there have been several alternative refrigerants developed with lower GWPs that can act as drop-in replacements. Two are considered in this scenario analysis, R32 and D2Y60. As the fluid in the vapor-compression cycle, refrigerant selection can significantly impact the coefficient of performance (COP) of the VRF system. The results of a study by Ling, et al., 2015

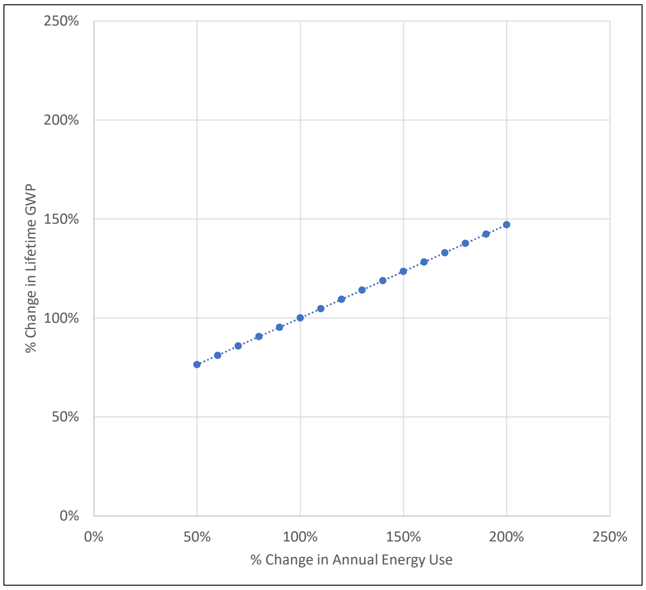

Figure 4. Sensitivity analysis results. A 10% change in system energy use results in a 5% shift in system carbon footprint.

(a)

Life Cycle Stage	R410A	R32	D2Y60
GWP (kg CO_2eq.)	989	677	271
COP[1]	4.16	4.02	4.27

[1] Ling, et al. 2015

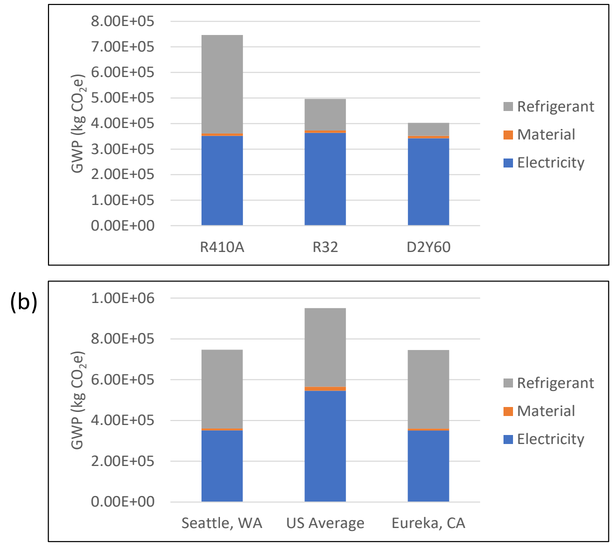

Figure 5. (a) Refrigerant sensitivity analysis details and results, (b) Regional scenario analysis results.

that simulates the COP of these alternative refrigerants were used to calculate differences in system energy use between the three refrigerants considered. Figure 5 (a) summarizes differences between GWP and COP for the three refrigerants, based on Ling, et al. 2015, and presents the results of the scenario analysis.

The COP for each of the refrigerants is similar, with slightly worse performance for R32 and slightly better performance for D2Y60 compared to R410A. The difference in GWP between the three refrigerants has a pronounced effect on the system carbon footprint, and use of R32 or D2Y60 decrease life cycle GHG emissions by 33% and 46% respectively.

REGIONAL VARIATIONS

The results of the LCA are applicable to a specific building in Seattle, Washington, operating in ASHRAE climate zone 4C (marine). In the United States, electricity grid mix and end-of-life recycling rates for materials vary widely geographically and so it is important to understand how the system carbon footprint may differ in other regions. It should be noted that insufficient data on refrigerant management during use and end-of-life was available to take any regional variations into account.

Two alternate scenarios were developed within the same ASHRAE climate zone as Seattle, to maintain consistency in expected system energy use. One scenario sited the system in Eureka, California and the second in a generic location with US-average electricity grid mix and recycling rates. Electricity grid mixes for the three scenarios are based on the US EPA's Emissions & Generation Resource Integrated Database (eGRID). End-of-life recycling rates for each scenario are determined based on construction and demolition waste diversion rates for Seattle, WA, Eureka, CA and for the US average Recycling rates in Seattle and Eureka are mandated by local building codes and are similar at 64% and 65%, respectively (Seattle Public Utilities 2018, California Building Standards Comission 2019). The US average recycling rate is 30% and is calculated from relevant material-specific diversion rates (United States Environmental Protection Agency 2018), weighted by the mass of each material in the mechanical equipment.

Figure 5 (b) presents the results of the scenario analysis. Grid permeation of hydropower in the Northwest and use of solar photovoltaic power and natural gas power plants in California decrease the impacts of electricity use on the system carbon footprint as compared to the US average. Decreased end-of-life equipment recycling rates for the US average lead to a small increase in the contribution of materials to the system carbon footprint.

ASSUMPTIONS AND LIMITATIONS

The main limitations of this study are associated with gaps in primary data collection, across the electricity, refrigerant and materials categories. Several of these limitations are addressed through sensitivity and scenario analysis. The applicability of energy model results to actual building operation is a limitation of this study, and this is explored through a sensitivity analysis that varies energy use over the system lifetime.

Another data gap is the lack of information on refrigerant emissions during end of life reclamation and destruction. These pathways may vary by region, but data was only available in California. In addition, refrigerant incineration emissions are approximated using NASA's CEA program, in the absence of actual incineration emissions from incineration facilities.

Determining material composition and quantities for the mechanical equipment is a challenge since this information is privately held by Mitsubishi. Material composition is based on a European EPD for a VRF outdoor unit, which results in uncertainty for the other system components such as the indoor units and branch controllers. Access to the actual bill of materials for the specific equipment installed would reduce uncertainty for the impact of equipment on the life cycle GWP. In addition, this study lacks data on procedures for equipment disassembly, which would affect the recyclability and end-of-life impacts of the individual materials.

The system lifetime is 15 years, so end-of-life flows and impacts occur a substantial amount of time after equipment manufacturing, construction and start-up. For this reason, any recycling is treated as open loop. Data for equipment recycling and refrigerant reclamation range from 2015 and 2018, while the expected system deconstruction is to take place in 2029 (15 years after system startup in 2014). End-of-life data may not be accurate for the future situation in which deconstruction and disposal take place.

SUMMARY

This study finds that for a VRF system installed at an office building in Seattle, Washington, electricity use and refrigerant emissions are the largest contributors to the system carbon footprint. The scenario analyses demonstrate variations in the system carbon footprint based on refrigerant selection and regional electricity grid mix differences. Using EUI as a metric does not account for almost half of the VRF system's carbon footprint. Designing the system to use low-GWP refrigerants can lower the whole system carbon footprint, as can advocating for deeper electricity grid decarbonization.

The findings of the sensitivity analysis suggest that variations in energy use can cause significant shifts in system carbon footprint. Therefore, it is important to have accurate energy use data when conducting an LCA on an HVAC system. As discussed in the Assumptions and Limitations section, data sources for this study could be refined in future work.

The results of this analysis are applicable only to the specific system installed in Seattle, Washington. To expand upon the scope of this study, the carbon footprint of HVAC systems should be considered in the context of whole building LCA. It is expected that the embodied carbon of system materials will be very small compared to embodied carbon of the building's structure and enclosure, however energy and refrigerant use can be significant contributors to the whole building carbon footprint.

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