JACOBS Consultancy

Water Consumption in US Petroleum Refineries

Final Report

Prepared for
Argonne National Labs

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Argonne National Labs

For Jacobs Consultancy

Rob Henderson

June 2016

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Executive Summary

Jacobs Consultancy has reviewed the consumption of water within US oil refineries. For the purposes of this study, “consumption” of water is defined as the amount of withdrawal water which is taken into the refinery’s fenceline boundaries and not returned to the environment in a liquid form, i.e., water which is chemically consumed plus water lost to evaporation.

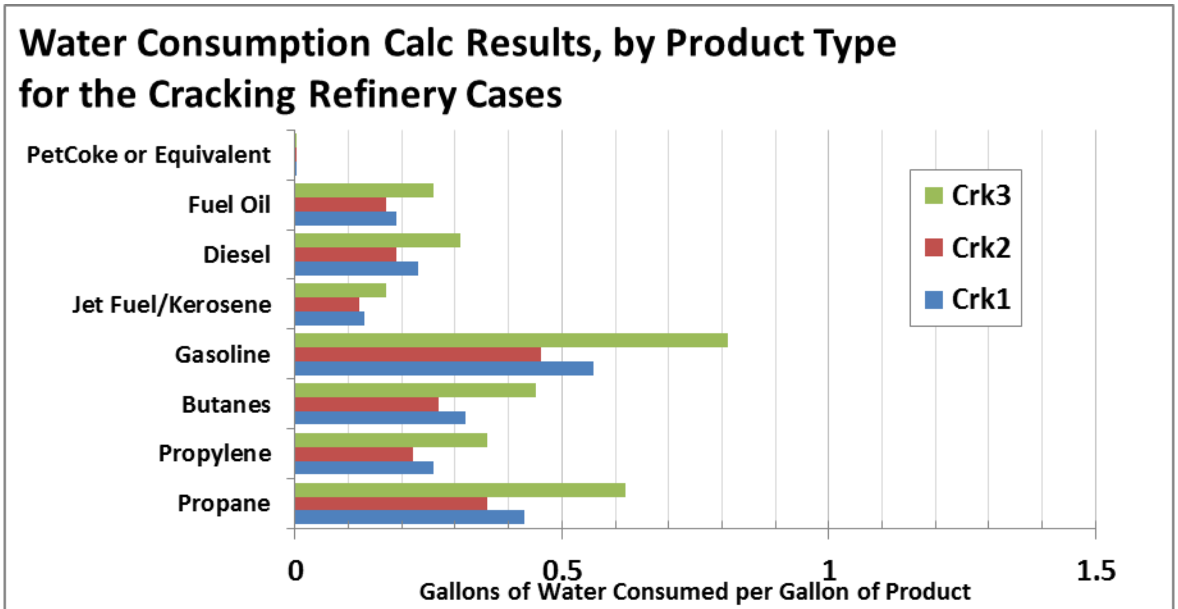
We sought to answer these following questions:

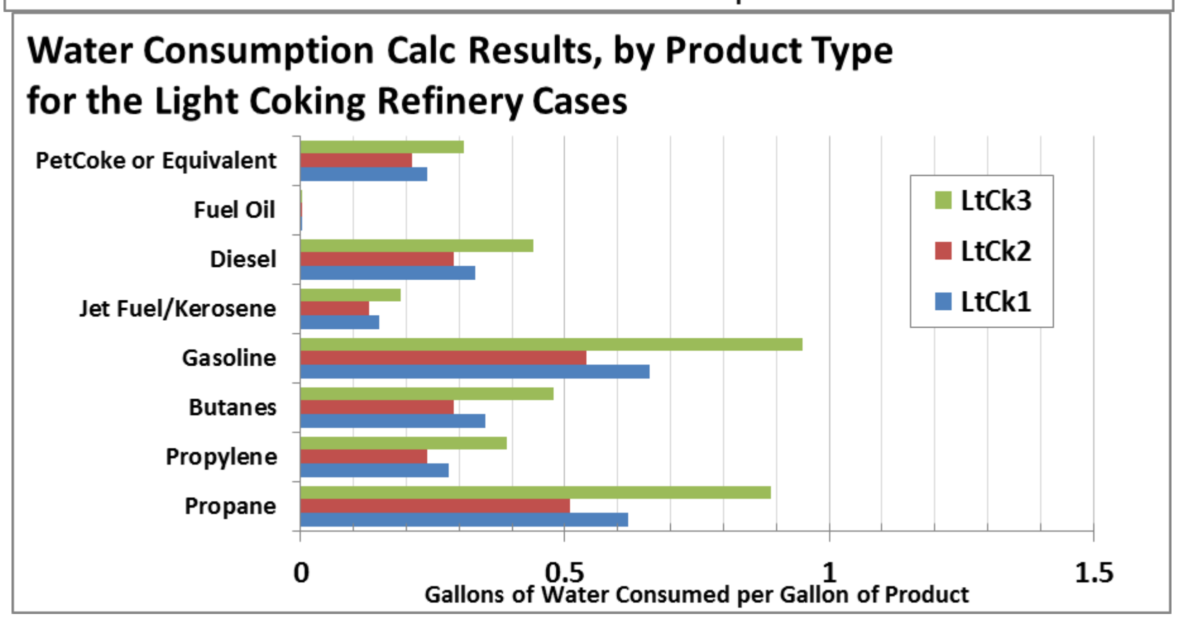
- What is the typical water consumption for an oil refinery? How does this vary based upon refinery design (both water-use efficiency and refinery complexity), crude oil gravity, and crude oil sulfur content?
- What is the typical makeup water source for refineries in the various PADDs?
- Can a specific water consumption amount be assigned to each refinery product, and if so, how much would this be?

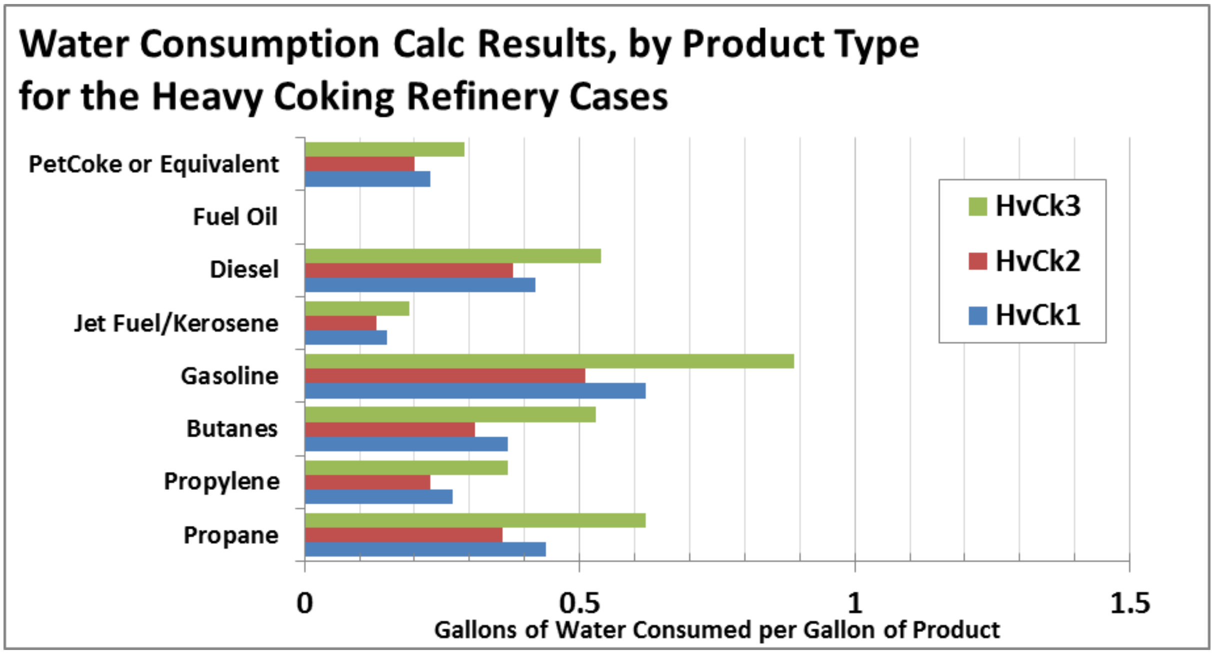
By developing models of three typical oil refineries and extrapolating from the results therein, the following conclusions can be drawn:

1. Oil refineries in the United States utilize makeup water from a variety of different sources, depending on their history, size, and geographic location. Most of this makeup water originates from surface water sources such as lakes and rivers, but a significant amount comes from groundwater resources, especially within PADD 2.
2. Increasing the size of a refinery (crude oil processing rate) will linearly and proportionally increase the volume of water consumed within the refinery since the water consumption is primarily related to process unit cooling water duty.
3. Increasing the complexity of a refinery by increasing the conversion level, or adding more process units, will increase the volume of water consumed consistent with the energy intensity of the processing units.
4. Increasing the sulfur content of the crude oil will increase the volume of water consumed within the refinery consistent with the hydrogen requirement for desulfurization.
5. Increasing the heaviness of the crude oil will directionally increase the volume of water consumed within the refinery as additional, more complex, and higher energy-intensive process units will be required to process the heavier oil.
6. Water evaporation from the cooling towers is the primary loss point within a refinery. This amount of evaporative loss is directly related to the process unit cooling water duty. Other water losses from steam traps, steam vents, boiler water blowdowns, and open topped coker and waste water treating plant (WWTP) holding areas contribute to water consumption at refineries, but are difficult to calculate from physical laws.

7. Water consumption within a refinery can be assigned to each product on a per barrel basis, bearing in mind the assumptions made in this exercise. The charts below show the range of water consumption for the various refineries' configurations studied, namely Cracking (Crk), Light Coking (LtCk), and Heavy Coking (HvCk).;







Note: Definitions and details of these cases are described in Table 2.

Study Introduction

Jacobs Consultancy Inc. (Jacobs Consultancy) completed a study for the US DOE in Winter 2015 (titled "Potential Vulnerability of US Petroleum Refineries to Increasing Water Temperature and/or Reduced Water Availability") on the uses of water within the US oil refining industry and the potential risks to this industry due to makeup water availability, temperature, and quality. Argonne National Labs (Argonne) reviewed this study, and found synergies between the refinery models developed in support of that study and work that Argonne has been pursuing to better understand the usage of water within US refineries. To leverage this previous effort, and to further Argonne's objectives, Argonne has engaged Jacobs Consultancy for a new study to investigate the consumption of water within US petroleum refineries.

For the purposes of this study, "consumption" of water is defined as the amount of withdrawal water which is taken into the geographic limits of a refinery and is not returned to the environment in a liquid form, i.e., water which is chemically consumed and water lost to evaporation. Small sections of the previous study may be directly repeated herein to complete this report.

Argonne is exploring questions such as:

- What is the typical water consumption for an oil refinery? How does this vary based upon refinery design (both water-use efficiency and refinery complexity), crude oil gravity, and crude oil sulfur content?
- What is the typical makeup water source for refineries in the various PADD's?
- Can a specific water consumption amount be assigned to each refinery product, and if so, how much would this be?

Background Discussion on Refinery Water Usage

A modern oil refinery is a complex, multi-technology, multi-process manufacturing facility which utilizes a significant amount of energy to process crude oil into finished products. As much as 10% of the energy content of crude oil is consumed within the processing steps, and a significant amount of this energy is subsequently rejected via thermal losses, fired heater stack gas heat loss, finfan air coolers, and cooling water heat exchangers. The heat rejected to cooling water is released to the atmosphere via contact with air and through water evaporation in the cooling towers.

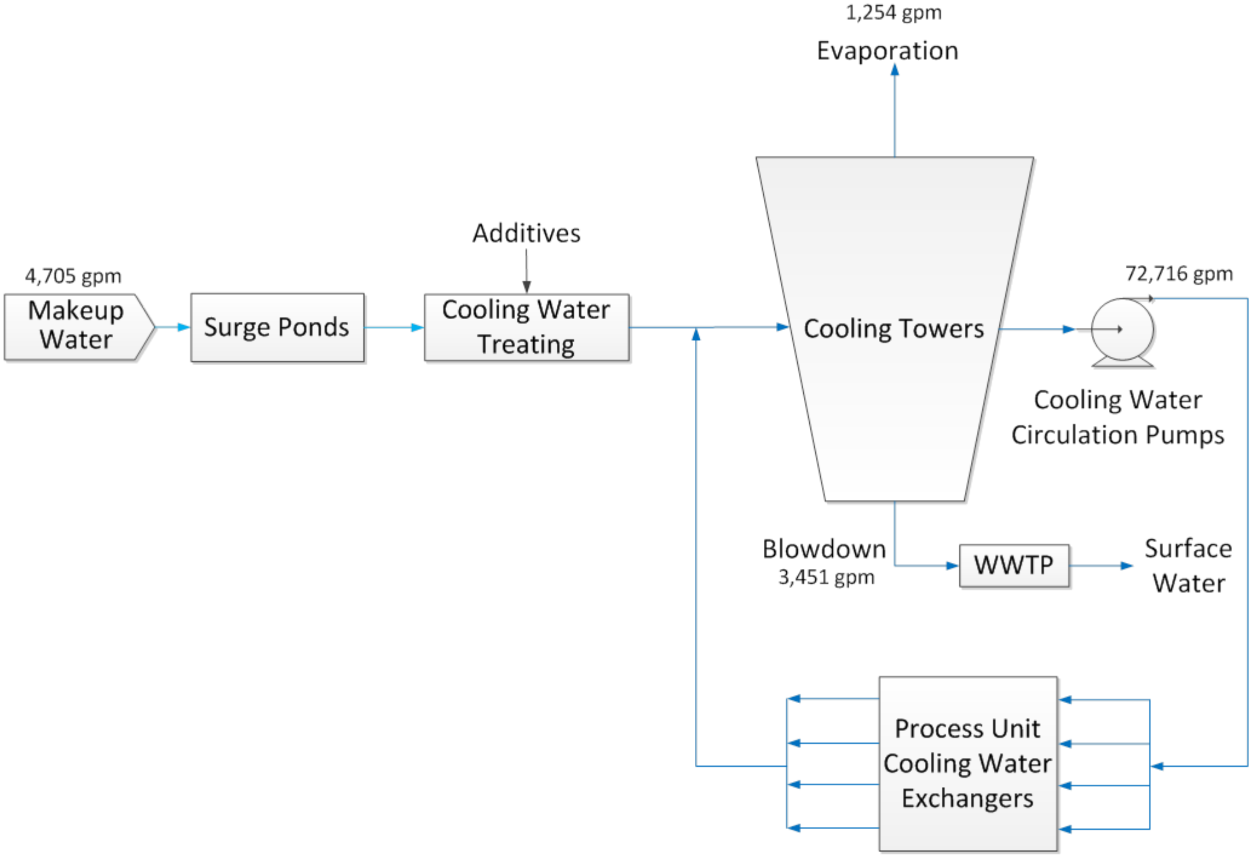
This cooling tower evaporation is the primary loss point for water within the refinery plant. Smaller volumes of evaporation also occur from steam trap blowdowns, steam vents, open holding tanks and ponds, Fluid Catalytic Cracking (FCC) regenerator offgas scrubbers, and

Delayed Coking unit water usage (coke pit and coke cutting-water holding tank evaporation). Chemical consumption of water within an oil refinery is found in the Steam Methane Reformer process where steam is utilized in the reformation process to produce hydrogen. Some refiners utilize concentration processes for makeup water purification and end up with a highly ionic brine solution which is typically injected in deep wells and is thus considered lost or consumed from the earth's surface water system. However, the prevalence of this water purification method within the United States is rare and is ignored for the purposes of this study.

A typical refinery "withdraws" (i.e., take in, purify, use within the process units or cooling water systems, treat, and then discharge to a local surface water body) about 1.5 barrels of fresh water to process 1.0 barrel of crude oil. However, water withdrawal, and subsequently consumption, can vary significantly between refineries, depending upon the design of the facility. A primary differentiator is whether the plant utilizes any once-through cooling water systems (systems which pump water from a body of water through cooling exchangers and then directly back into the water body, rather than recirculating through a closed-loop system). The once-through cooling system "withdraws" a large amount of water, but "consumes" less water compared to facilities using recirculating cooling tower systems. This is due to the fact that the once-through cooling system rejects the heat to a significantly large body of thermal mass (e.g., river or lake), and thus results in small temperature increase with much less net increase in evaporative losses compared to evaporative losses when rejecting the same amount of heat using cooling towers.

As the cooling tower evaporation loss is the largest consumer of water within a refinery (approximately 80-90% of the total), a large portion of this study's discussion is focused on the evaporative losses within cooling towers. Figure 1 shows a typical cooling water balance for an oil refinery's cooling tower.

Figure 1: Refinery Closed Loop Cooling Tower Water Balance Example



The makeup water comes from varying sources while the blowdown water is routed to the waste water treating plant and subsequently back to a surface body of water.

Refinery Water Sources

There are several primary water sources for refineries: "fresh" surface water (lakes, rivers, ponds), "fresh" ground water (aquifers). Water from aquifers normally is accessed by drilling wells, with surface water being directly pumped out of the water body. The actual direct source of the makeup water to the refinery can be any one or a combination of these sources:

- *City or municipal water district (fresh water), which could be sourced from surface water and/or ground water (~60%***** of refineries)*
- *Ground water (~15%)*
- *Once-through sea water (~5%)***
- *Once-through river/lake water (~10%)*
- *River water (~50%)*

- *Lake water (<5%)*

**** as a percentage of the top 135 US oil refineries, not on a barrel capacity basis***

***** usage of sea water for cooling is extremely capital intensive due to the highly-corrosive and fouling nature of salt water and most refiners have gone away from this usage***

the numbers add up to >100% due to many refiners having more than one source of makeup water

The previously completed high-level analysis was reviewed and extended to identify the primary water source for refineries on *a barrel of oil capacity basis* within each PADD. Once-through water usage (sea or fresh) was excluded, due to its small and shrinking usage and because the focus of the study is to quantify "fresh" water consumption, therefore the only water sources considered in this study for the refineries were: 1) surface water (lake or river), 2) city/municipal, and 3) ground water. About 40% of the water sources for refineries were known while the rest were estimated based on the facility's size and geographic location (e.g., within a city limits, in a dry region, on a river or major lake). Based upon this analysis, we estimated the following water source shares (on a barrel basis) for the three largest PADDs (Petroleum Administration for Defense Districts, five regions into which the United States can be divided):

- PADD 2 (Midwest): ~76% River/Lake, ~22% Ground, ~2% City/Municipal,
- PADD 3 (Gulf Coast): ~82% River, ~7% Ground, ~11% City/Municipal,
- PADD 5 (West Coast): ~43% River, ~8% Ground, ~49% City/Municipal,

This results in an overall split in the United States for all five PADDs of ~72% River/Lake, ~10% Ground, and ~18% City/Municipal (accurate to ±10%). These numbers indicate a larger usage of river/lake water than was reported in the previous study, primarily as this review was done on a crude oil barrel capacity basis, plus most of the larger refineries tend to use water directly from a lake or river, while more of the smaller ones at least partially utilize city water. City/Municipal water is ultimately sourced from ground or surface water bodies, but the distribution of these water sources for City/Municipal water was not reviewed as part of this study.

Study Objectives

In this study, we modeled and discussed the consumption of water within the US petroleum refining industry. The amount of water consumption for any specific refinery can vary significantly. Consequently, we developed some "typical" refineries to model and then based our discussion upon the expected range of water consumption for these facilities. The actual water consumption at any one particular facility will differ from the results given here, but, based upon our experience, they are representative of the industry on average.

As discussed above, water is lost or consumed in a number of different ways within a refinery. The primary loss points are (in relative order of decreasing volume):

1. Water vapor to atmosphere from the top of cooling water towers, (was calculated for this study)
2. Water vapor from steam traps, steam vents, open sewers, Delayed Coker unit equipment (open-roofed water tanks, coke handling area, drum venting, etc.), and open-roofed waste water treating plant equipment, (was estimated for this study)
3. Chemical consumption of water within Steam Methane Reformer(s) (calculated), and
4. Water vapor from the flue stack of FCC Regenerator offgas scrubber(s). (not considered for this study, see below)

The quantity of water lost from cooling towers can be calculated based upon the heat balance of the cooling water system. These calculations will be discussed and shown in more detail below. Water vapor losses from steam traps, steam vents, open sewers, Delayed Coker unit equipment, and open-roofed waste water treating plant equipment are more difficult to quantify. Based upon our operating and design experience and the recent interviews which were conducted in support of the DOE study, we have estimated a factor of 20% of total cooling tower losses to represent these losses for a non-coking refinery with an additional factor added on for the coking refineries.

Chemical consumption of water within Steam Methane Reformer(s) can be calculated based upon the stoichiometric requirements (2730 gallons of water is consumed per 1.0MMscf of pure H2 produced, this is less than the stoichiometric calculation of the 100% conversion to CH4 and H2O to H2 and CO2 as a portion of the CH4 is only converted to CO, which is then burned as fuel). Water vapor loss from the stack of FCC Regenerator offgas scrubber(s) can also be calculated, but since 1) not all refineries have FCCs, 2) not all FCCs have scrubbers, and 3) the scrubbers' actual operating design (affecting the equilibrium temperature of the system's water and thus water vaporization quantity) can vary significantly, we have not ascribed any additional water loss to this specific cause, but would expect it to be relatively small compared to the total estimate generated by combining all of the other consumers. Some liquid water also leaves the refinery absorbed onto petcoke product, but this was not accounted for as it technically is still in liquid form and is part of the product which is being sold. It also would be a small quantity; if for example the petcoke leaving the heavy coking refinery were 10% water by weight, then that would be equivalent to a "loss" of 32gpm.

Refinery Modeling

For this Study we utilized previous Jacobs Consultancy and Argonne work (Han, J., Elgowainy, A., Wang, M.Q., DiVita, V.B., 2015. Well-To-Wheels Analysis of High Octane Fuels with Various Market Shares and Ethanol Blending Levels (No. ANL/ESD-15/10), Argonne National Laboratory, Argonne, IL.) to establish the configuration, process unit size, and production volumes for three "typical" refinery configurations of medium-sized (120mbpd) refinery configurations processing three distinctly different crude oil types. These cases were defined as:

- A "Cracking" refinery processing sweet, light crude oil with an API gravity of 42.4 and a 0.4wt% sulfur content,
- A "Light Coking" refinery processing medium sour crude oil with an API gravity of 30.9 and a 2.0wt% sulfur content, and
- A "Heavy Coking" refinery processing heavy sour crude oil with an API gravity of 25.9 and a 2.8wt% sulfur content.

The model refineries' process units and the units' capacities are listed below.

Table 1: Process Unit Capacities of Representative Refineries

	Units	Cracking Refinery	Light Coking Refinery	Heavy Coking Refinery
		Capacity	Capacity	Capacity
Process Units				
Crude (incl. Sat Gas Plant)	BPSD	**120000**	**120000**	**120000**
Vacuum Unit	BPSD	**35014**	**51908**	**59858**
Naphtha Hydrotreater	BPSD	**22623**	**21693**	**22671**
Catalytic Reformer	BPSD	**22397**	**21476**	**22444**
Isom Naphtha Hydrotreater	BPSD	**3,381**	**2,400**	**2,400**
C5 Isom	BPSD	**3,347**	**2,376**	**2,376**
BenSat	BPSD	**6,538**	**5,509**	**8,727**
Jet Merox	BPSD	**11,950**	**8,995**	**9,133**
Diesel Hydrotreater	BPSD	**42,243**	**51,815**	**35,191**
Hydrocracker	BPSD	**0**	**0**	**31,110**
Delayed Coker	BPSD	**0**	**27,380**	**33,720**
Gas Oil Hydrotreater	BPSD	**0**	**19,439**	**20,529**
FCC (incl. UnSat Gas Plant)	BPSD	**26,655**	**34,800**	**24,749**
FCC Naphtha Hydrotreater	BPSD	**14,346**	**16,800**	**12,344**
Alkylation Unit	BPSD Alkylate	**4,866**	**6,254**	**4,792**
Hydrogen Plant	MM SCFD H2	**0**	**32**	**86**
Offsites				
Sulfur Plant	Tons/day	**28**	**272**	**384**
Amine Regeneration	MM SCFD acid gas	**1**	**9**	**12**
Sour Water Stripper	MLB/h	**250**	**300**	**350**
Miscellaneous				

Utilities				
Deaerators	MLB BFW	**1144**	**1144**	**1144**
Demineralizer Plant	MLB/h	**477**	**477**	**477**
WWTP				

Table Notes:

- BPSD = Barrels of oil Processed per Standard Day
- No aromatics recovery units, solvents, lube oils, or asphalt sales
- No Cogen
- No fuel gas sales
- No Cryogenic unit to increase C3/C4 recovery
- No imported hydrogen (H2)
- Natural gas purchased from the local utility for fuel gas
- Products: propane, propane/propylene mix, butanes, regular and premium gasoline, jet/kerosene fuel, ultra-low sulfur diesel (ULSD), fuel oil, petroleum coke, and molten sulfur

We used these model results to better understand the gross usage of cooling water, the effects of the original process unit design on consumption, and to determine what portion of water loss could be ascribed to each hydrocarbon product. The cooling water circulation rates were developed from actual process unit operating data to reflect a "typical" design basis for each of the process units. However, the amount of cooling water (CW) required for any one process unit can vary significantly based upon a number of different factors which prevailed during the initial design of the process unit:

- The size of the process unit (smaller units may not have finfans upstream of cooling water exchangers due to their cost, thus increasing the cooling water exchangers' required duty)
- The relative cost of electricity versus capital (if electricity and capital are both cheap, then finfans may be more prevalent)
- The cost and availability of water in the facility's location (if water is limited or expensive, then finfans may be more prevalent and/or have higher duties, thus requiring less CW)

Additionally, the current condition and performance of the aircoolers and cooling water exchangers within the facility will change with ambient conditions and throughout the normal process unit's maintenance cycle. To reflect this variability in usage of CW (and the subsequent amount of water which will be lost via evaporation), two additional cases were developed for each of the three refinery configurations: "efficient" facilities which utilize 20% less cooling water and "less efficient" operations which utilize 50% more CW than the base facility. The minus 20% factor was chosen to be representative for a more efficient operation as a reduction in required cooling water duty in this range has been realistically seen in newly designed facilities, but not much lower could be achieved in this area without a significant focus on minimizing water use, something which has rarely been economic within the US at the time of these plants' construction. The plus 50% factor was chosen since we are familiar with facilities which have extremely stressed cooling tower systems with high cooling water return temperatures due to fouling in upstream exchangers and/or an original design preference to minimize the usage of upstream finfan air coolers.

This sensitivity yielded a total of nine separate refinery cases to work with. See Table 2 for their designations.

Table 2: Refinery Matrix

	Refineries	Type of Refinery
Typical CW usage	Crk1	Cracking
20% lower usage than typical	Crk2	Cracking
50% higher usage than typical	Crk3	Cracking
Typical CW usage	LtCk1	Light Coking
20% lower usage than typical	LtCk2	Light Coking
50% higher usage than typical	LtCk3	Light Coking
Typical CW usage	HvCk1	Heavy Coking
20% lower usage than typical	HvCk2	Heavy Coking
50% higher usage than typical	HvCk3	Heavy Coking

Water Consumption Assigned to each Refinery Hydrocarbon Product

The amount of cooling water which each process unit utilizes was calculated based on formulas ratioed from the unit feed rates. These formulas have been developed by Jacobs Consultancy as being "typical" from actual refinery operating data and unit design data.

Table 3: Base Cooling Water Usage for Representative Refineries

	Cracking Refinery	Units	Cooling Water (CW)	Light Coking Refinery	CW	Heavy Coking Refinery	CW
	Capacity		GPM	Capacity	GPM	Capacity	GPM
<u>Process Units</u>							
Crude (incl. Gas Plant)	120000	BPSD	6333	120000	6333	120000	6333
Vacuum Unit	35014	BPSD	3112	51908	4614	59858	5321
Naphtha HT	22623	BPSD	1100	21693	1055	22671	1102
Reformer	22397	BPSD	9456	21476	9068	22444	9476
Isom NHT	3,381	BPSD	164	2,400	117	2,400	117
C5 Isom	3,347	BPSD	163	2,376	116	2,376	116
BenSat	6,538	BPSD	318	5,509	268	8,727	424
Jet Merox	11,950	BPSD	0	8,995	0	9,133	0
Diesel HT	42,243	BPSD	4107	51,815	5038	35,191	3421
Hydrocracker	0	BPSD	0	0	0	31,110	4321
Delayed Coker	0	BPSD	0	27,380	2662	33,720	3278
GOHT	0	BPSD	0	19,439	945	20,529	998
FCC (incl. Gas Plant)	26,655	BPSD	9218	34,800	12035	24,749	8559
FCC NHT	14,346	BPSD	697	16,800	817	12,344	600
Alky	4,866	BPSD Alkylate	14665	6,254	18848	4,792	14444
Hydrogen Plant	0	MM SCFD H2	0	32	1129	86	2999
<u>Offsites</u>							
Sulfur Plant	28	LT/d	0	272	0	384	0
Amine Regen	1	MM SCFD Acid Gas	500	9	1000	12	1200
SW Stripper	250	MLB/hr	500	300	750	350	1000
Misc.	0	-	4000	0	4000	0	4000
<u>Utilities</u>							
Deaerators	1144	MLB BFW	0	1144	0	1144	0
Demin Plant	477	MLB/hr	1000	477	1000	477	1000
WWTP			3000	0	3000	0	3000
Totals:			58334		72793		71709

From the required cooling water circulation rates and duty, an expected loss from evaporation for each unit was then calculated based upon an expected cooling water "send" and "return" temperature (kept constant for all of the process units). This amount of evaporation was then split between each of the refinery's primary hydrocarbon products: propane, propylene, butanes, gasoline, jet/kerosene, diesel, fuel oil, and petroleum coke (coke), as described below:

- CDU: the crude unit's water consumption was split between all of the refinery's products, ratioed to the refinery's total production volume in actual barrels.
- VDU: the vacuum unit's water consumption was split between the unit's primary products: gas oil (which was then split two-thirds to gasoline and one-third to diesel) and residual fuel oil ratioed to the refinery's total production volume. For the refinery configurations which include a coker to process the fuel oil, this unit's water consumption was split two-thirds to gasoline and one-third to diesel.
- NHT: the naphtha hydrotreating unit's water consumption was assigned to gasoline.
- Reformer: the catalytic reforming unit's water consumption was primarily assigned to gasoline, but with 4% assigned to propane and 1% to butanes due to these products being co-produced in the unit. More than 1% of the unit's feedrate becomes butanes within this unit, but the iC4 produced in this unit is consumed in the Alky and a portion of the nC4 is blended into gasoline, so the rest of the factor which could be assigned to butanes was instead re-assigned to the gasoline product. The unit also produces a large amount of hydrogen which is utilized in the hydrotreaters.
- Isom NHT: the Isom NHT's water consumption was assigned to gasoline.
- Isom: the C5 isomerization unit's water consumption was assigned to gasoline.
- BenSat: the benzene saturation unit's water consumption was assigned to gasoline.
- DHT: the diesel hydrotreating unit's water consumption was assigned to diesel (ULSD).
- FCC/GOHT: the FCC and the gasoil hydrotreating units' water consumption was split among the products typically yielded from an FCC unit via these typical ratios: with 3% assigned to propane, 7% to propylene, 2% to butanes, 2% to fuel oil, and the final 81% being split three-fourths to gasoline and one-fourth to diesel. More than 2% of the unit's feedrate becomes butanes within this unit, but the butylenes produced in this unit are consumed in the Alky and a portion of the other C4's are blended into gasoline, so the rest of the factor which could be assigned to butanes was instead re-assigned to the gasoline product. For the refinery configurations which destroy fuel oil in the coker, the extra 2% for fuel oil was split three-fourths to gasoline and one-fourth to diesel.
- FCC NHT: the FCC naphtha hydrotreating unit's water consumption was assigned to gasoline.

- Hydrocracker: the hydrocracking unit's water consumption was split among the products typically yielded from an HC unit via these typical ratios: with 3% assigned to propane, 4% to butanes, 32% to gasoline, and 57% to diesel. More than 4% of the unit's feedrate becomes butanes within this unit, but the iC4 produced in this unit is consumed in the Alky and a portion of the other C4's are blended into gasoline, so the rest of the factor which could be assigned to butanes was instead re-assigned to the gasoline product.

- Delayed Coker: the coking unit's water consumption was split among the products typically yielded from a coker via these expected ratios: with 35% to gasoline, 35% to diesel, and 30% to coke. To put all of the refinery's products on a liquid volume basis, the coker's petroleum coke was "converted" into a fuel oil barrel energy equivalent at the ratio of 1.0 metric tonne of coke equals 5.5 barrels of actual liquid.

- Alky: the alkylation unit's water consumption was assigned to gasoline.

- SMR: the steam methane reforming unit's water consumption was assigned 100% to diesel since the catalytic reformer (which was mostly ascribed to gasoline) produces enough hydrogen to fully produce and process gasoline and the additional hydrogen required from the SMR is to be utilized to produce diesel in the DHT and Hydrocracker.

- The common utility units and miscellaneous units' water consumption was split between all of the refinery's products, ratioed to the refinery's total production volume (the same as the crude unit).

The additional water consumption assigned for steam traps, steam venting, WWTP pond evaporation, etc. was also split between all of the refinery's products, ratioed to the refinery's total production volume. For all of the refineries this water consumption volume was assumed to be 20% of the base refinery's total water volume consumed in the cooling towers. For the refineries which included Cokers and SMRs, there were additional factors applied to the Coker and the SMR to account for the additional water evaporation from the Coker's tanks and petcoke pit (this consumption was assigned per the above Coker cooling water evaporation ratios) and the chemical consumption of water within the SMR (this volume was assigned to diesel since most of the hydrogen produced from the SMR is consumed within the DHT, GOHT, and Hydrocracker to produce diesel). The results of all of these calculations are shown below in Tables 4 and 5 for the Cracking Refinery Base Case. Details of the other eight refinery cases are included in the Appendix A.

Table 4: Water Consumption Calculation Example Table: Crk1 Refinery Base Case

Process Units	CW Circ, gpm	CW Evap, gpm	C3	C3=	Butane	Gasoline	Jet	Diesel	Fuel Oil	Coke
Crude (incl. Gas Plant)	6333	106.4	1.2	2.7	0.8	41.8	11.0	37.2	11.8	0
Vacuum Unit	3112	52.3	0	0	0	22.1	0	11.0	19.2	0
Naphtha HT	1100	18.5	0	0	0	18.5	0	0	0	0
Reformer	9456	158.9	6.4	0	1.6	150.9	0	0	0	0
Isom NHT	164	2.8	0	0	0	2.8	0	0	0	0
C5 Isom	163	2.7	0	0	0	2.7	0	0	0	0
BenSat	318	5.3	0	0	0	5.3	0	0	0	0
Jet Merox	0	0	0	0	0	0	0	0	0	0
Diesel HT	4107	69.0	0	0	0	0	0	69.0	0	0
Hydrocracker	0	0	0	0	0	0	0	0	0	0
Delayed Coker	0	0.0	0	0	0	0	0	0	0	0
GOHT	0	0.0	0	0	0	0	0	0	0	0
FCC (incl. Gas Plant)	9218	154.9	4.6	10.8	3.1	101.8	0.0	31.4	3.1	0
FCC NHT	697	11.7	0	0	0	11.7	0	0	0	0
Alky	14665	246.4	0	0	0	246.4	0	0	0	0
Hydrogen Plant	0	0	0	0	0	0	0	0	0	0
Offsites										
Sulfur Plant	0	0	0	0	0	0	0	0	0	0
Amine Regen	500	8.4	0.1	0.2	0.1	3.3	0.9	2.9	0.9	0
SW Stripper	500	8.4	0.1	0.2	0.1	3.3	0.9	2.9	0.9	0
Misc.	4000	67.2	0.7	1.7	0.5	26.4	6.9	23.5	7.4	0
Utilities										
Demin Plant	1000	16.8	0.2	0.4	0.1	6.6	1.7	5.9	1.9	0
WWTP	3000	50.4	0.5	1.3	0.4	19.8	5.2	17.6	5.6	0
	58334	**980.0**	13.8	17.4	6.6	663.5	26.5	201.4	50.8	0

The results of dividing this water consumption between the nine typical refinery product streams are shown in Table 5 below.

Table 5: Water Consumption Calculation Example Table, Summation for Each Product

Crk1 Refinery Base Case		Loss, gpm	C3, gpm	C3=, gpm	Butanes, gpm	Gasoline, gpm	Jet, gpm	Diesel, gpm	Fuel Oil, gpm	Coke, gpm
CW Evaporation Totals for each Product, gpm		980	13.8	17.4	6.6	663.5	26.5	201.4	50.8	0
	All Other Loss, gpm	196	2.1	5.0	1.4	77.1	20.2	68.5	21.7	0
Totals per product, gpm:		1176	15.9	22.5	8.0	740.6	46.7	269.8	72.4	0
Gallons H2O lost / bbl product:			18.2	10.9	13.5	23.4	5.6	9.6	8.1	0
Gallons H2O lost / gal product:			0.43	0.26	0.32	0.56	0.13	0.23	0.19	0

Thus, a gallon of gasoline production requires 0.56 gallons of water to be consumed within this refinery. For comparison purposes, the volume of water required increases to 0.66 gallons for the LtCk1 refinery and to 0.62 gallons for the HvCk1 refinery. Gasoline is a highly processed fuel and therefore utilizes the most water per barrel to process it for production. However, only slightly more processing is required as the sulfur content of the refinery's crude oil increases, so the consumption doesn't increase very much with the heavier refinery configurations. Diesel production requires 0.23, 0.33, and 0.42 gallons, respectively, for the three refinery models. This water consumption does increase significantly as the crude oil becomes more sour due to the high severity hydrotreating which ULSD requires as the unit's feeds become heavier and more sour. The total water consumption expected for each refinery type is shown in Table 6 below.

Table 6: Water Consumption Calculation Results, by Refinery Type

	Refineries	Total Consumption, gpm
Typical	Crk1	1176
20% lower usage than typical	Crk2	980
50% higher usage than typical	Crk3	1666
Typical	LtCk1	1548
20% lower usage than typical	LtCk2	1303
50% higher usage than typical	LtCk3	2159
Typical	HvCk1	1639
20% lower usage than typical	HvCk2	1398
50% higher usage than typical	HvCk3	2241

The resulting matrix of water consumption required for each barrel of product produced and for each reviewed refinery configuration is included below in Tables 7, 8, and 9.

Table 7: Water Consumption Calc Results, by Product Type for the Cracking Refinery Cases, Gallons of Water Consumed per Gallon of Product

	Crk1	Crk2	Crk3
Propane	0.43	0.36	0.62
Propylene	0.26	0.22	0.36
Butanes	0.32	0.27	0.45
Gasoline	0.55	0.46	0.81
Jet Fuel/Kerosene	0.13	0.12	0.17
Diesel	0.23	0.19	0.31
Fuel Oil	0.19	0.17	0.26
PetCoke	N/A	N/A	N/A

Table 8: Water Consumption Calc Results, by Product Type for the Light Coking Refinery Cases, Gallons of Water Consumed per Gallon of Product

	LtCk1	LtCk2	LtCk3
Propane	0.62	0.51	0.89
Propylene	0.28	0.24	0.39
Butanes	0.35	0.29	0.39
Gasoline	0.66	0.54	0.95
Jet Fuel/Kerosene	0.15	0.13	0.19
Diesel	0.33	0.29	0.44
Fuel Oil	N/A	N/A	N/A
PetCoke (equivalent basis)	0.24	0.21	0.31

Table 9: Water Consumption Calc Results, by Product Type for the Heavy Coking Refinery Cases, Gallons of Water Consumed per Gallon of Product

	HvCk1	HvCk2	HvCk3
Propane	0.44	0.36	0.62
Propylene	0.27	0.23	0.37
Butanes	0.37	0.31	0.53
Gasoline	0.62	0.51	0.89
Jet Fuel/Kerosene	0.15	0.13	0.19
Diesel	0.42	0.38	0.54
Fuel Oil	N/A	N/A	N/A
PetCoke (equivalent basis)	0.23	0.20	0.29

With the limitations previously stated about the assumptions utilized in the modeling effort, some broad conclusions can be drawn about the consumption of water for producing the above refinery products:

- Gasoline requires the most processing and thus the most water consumption
- As the complexity of the refinery increases, so does the water consumption
- As the heaviness/sourness of the crude oil increases, so does the water consumption
- Jet Fuel/Kerosene production requires the lowest amount of water consumption of the major products due to the minimal amount of processing which it requires

Refinery Size Discussion

The work done in support of this study indicates that water consumption will increase roughly in proportion to an increase in its overall crude processing capacity. This is due to the water consumption in each process unit being proportional to the unit's cooling water duty requirement and this CW duty is directly proportional to the process unit size. Hence, a 240 kbpd refinery will consume essentially twice as much water as our base case 120 kbpd facility.

Refinery Complexity Discussion

A refinery's complexity is typically measured by its Nelson Complexity Index (NCI). As a refinery becomes more complex (i.e., has higher levels of conversion or new process units added to it for additional processing steps), the consumption of water will directionally increase. As refineries which have the same NCI can actually have different configurations, the relationship between NCI and water consumption cannot be definitively quantified any further than this.

Overall Conclusions

1. Oil refineries in the United States utilize makeup water from a variety of different sources, depending on their history, size, and geographic location. Most of this makeup water originates from surface water sources such as lakes and rivers, but a significant amount comes from groundwater resources, especially within PADD 2.
2. Increasing the size of a refinery (crude oil processing rate) will linearly and proportionally increase the volume of water consumed within the refinery since the water consumption is primarily related to process unit cooling water duty.
3. Increasing the complexity of a refinery by increasing the conversion level, or adding more process units, will increase the volume of water consumed consistent with the energy intensity of the processing units.

4. Increasing the sulfur content of the crude oil will increase the volume of water consumed within the refinery consistent with the hydrogen requirement for desulfurization.

5. Increasing the heaviness of the crude oil will directionally increase the volume of water consumed within the refinery as additional, more complex, and higher energy-intensive process units will be required to process the heavier oil.

6. Water evaporation from the cooling towers is the primary loss point within a refinery. This amount of evaporative loss is directly related to the process unit cooling water duty. Other water losses from steam traps, steam vents, boiler water blowdowns, and open topped coker and waste water treating plant (WWTP) holding areas contribute to water consumption at refineries, but are difficult to calculate from physical laws.

7. Water consumption within a refinery can be assigned to each product on a per barrel basis, bearing in mind the assumptions made in this exercise.

Appendix A.

Water Consumption Results for the Nine Refinery Permutations