FEEDSTOCK SOURCING YEARS 4 AND 5

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ATJ	alcohol-to-jet
BDST	bone dry short tons – 2,000 pounds
CDW	construction and demolition waste
FHR	forest harvest residuals – the tree parts left on a commercial softwood timber harvest after removal of primary timber crop, that is, merchantable logs (sawlogs and sometimes pulpwood logs)
IBA	isobutyl alcohol
IPK	isoparaffinic kerosene – bio-jet fuel
MBS	mild bisulfite
PNW	Pacific Northwest – for the NARA project region this includes Washington, Oregon, Idaho, and the western half of Montana
TEA	Techno-Economic Analysis
TPO	Timber Products Output system

EXECUTIVE SUMMARY

Of all the possible softwood resources in the PNW, the one that is currently underutilized and widely available at significant scale (and thus available at the most favorable cost to the conversion facility) is softwood forest harvest residuals. There are at least three most promising geographic areas on the west side of Oregon and Washington where a full-scale greenfield integrated biorefinery could find sufficient sustainable FHR feedstock (approximately 1 million BDST per year) within reasonable hauling distances (about 60 miles). It is estimated that these feedstocks (FHR) can be delivered at about $62/BDST and have been shown via lab and pilot scale tests to be acceptable for the NARA process.

INTRODUCTION

The Feedstocks Logistics – Sourcing Task efforts for NARA project years 1-3 were completed under auspices of Weyerhaeuser Company (WY), and have been reported elsewhere (Marrs et al., 2015) so will not be repeated here. For project years 4 and 5, these tasks were done under contract with Gevan Marrs, LLC.

The year 4 and 5 major tasks were:

- Collect and characterize a few remaining key FHR sources, including those used in the “1,000 gallon biojet” production task.
- Obtain and prepare suitable quantities and quality of FHR feedstock and pre pare it for the 1,000 gallon biojet production task.
- Summarize and report all tested feedstocks and comment on NARA process economic sensitivity to key characteristics (size, moisture, chemical composition).

TASK 1: ADDITIONAL FEEDSTOCKS CHARACTERIZATION

Four additional feedstock samples were characterized in the Year 4 & 5 project work (all of these were part of the collection and preparation of large quantities for the 1,000 gallon biojet production task (Wooley et al., 2016)).

The four samples were:

- FS-17[1] "Siuslaw 900 Douglas-fir" - FHR from Douglas-fir timber harvest on WY land near Eugene, OR.
- FS-18 "CSKT Montanan Int Douglas-fir" – FHR from interior Douglas-fir timber harvest on Consolidated Salish-Kootenai Tribal (CSKT) lands near Polson, MT.
- FS-19 "Muckleshoot Enumclaw WA FHR" – FHR from Douglas-fir timber harvest on Muckleshoot tribal land near Enumclaw, WA.
- FS-20 "1,000 gal biojet feedstock blend" – A blend of about 90% FS-17, 5% each of FS-18 and FS-19. Used as the woody feedstock for the 1,000 gal biojet effort.

In contrast to prior samples that were taken from as-ground material and shipped to WY Technology Center for fines and oversize screening (Marrs et al., 2015), each of these materials was screened and prepared in the Lane Forest Products yard outside Junction City, OR. Only prepared accepts material was sampled and sent to WY Analytical and Testing lab for compositional characterization. Results of the complex screening and resizing trials, in order to meet demands of the ZeaChem pretreatment system, are detailed in Appendix 2 of this report.

Adding these characterization results to the previously reported feedstocks results in the summary database table shown in Table FS2-1.1. The chemical composition database for all samples tested is shown in Table FS2-1.2. (All these results are available in Excel spreadsheet located at https://research.libraries.wsu.edu/xmlui/handle/2376/6460.

Comparisons of all tested samples for polysaccharides, lignin, ash and extractives are shown in Figures FS2-1.1 through -1.4, respectively.

Note that for most samples, the screened accepts ("A" suffix) and screen fines ("F" suffix) samples were tested separately. The rationale for screening out the fines and sending them to hog fuel to burn for energy production is apparent when comparing the typical lower polysaccharides, higher lignin, higher extractives and *much* higher ash content of fines. This arises from a concentration of inorganics (from soil contamination) in the fines as well as a much higher proportion of bark particles in the fines—leading to higher lignin and extractives. While it is not feasible to assess the specific economic impact of the fines on product quantities and value, and in particular it is difficult to assess impact of inorganics (ash), it is believed (from experience in the pulp and paper industry) that removal of some portion of fines will be warranted.

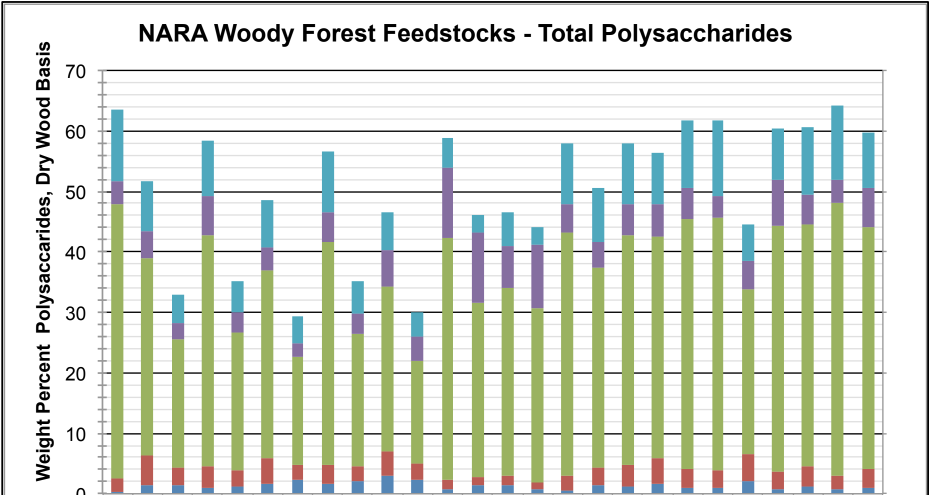
Table FS2-1.1. Summary screening results, bark and ash content of NARA feedstocks.

Summary Key Qualtiy Aspects NARA Feedstocks	NARA Feedstocks Tracking.xlsx		
Feedstock	Percent Fines Reject	Wet basis Moisture Content	Bark Content
NARA-FS-01 SW WA Douglas-fir Reference Wood Chips		53.9%	1.4%
NARA-FS-02 SW WA Hem/Spruce Forest Residuals Accepts		39.1%	9.5%
NARA-FS-02 SW WA Hem/Spruce Forest Residuals Fines	22.0%		NM
NARA-FS-03 NW OR Dfir Forest Residuals Accepts		38.1%	3.5%
NARA-FS-03 NW OR Dfir Forest Residuals Fines	14.8%		NM
NARA-FS-04 N OR Coast Forest Residuals Accepts		61.9%	11.3%
NARA-FS-04 N OR Coast Forest Residuals Fines	16.1%		NM
NARA-FS-05 King/Horse Cr Doug-fir / Cedar Accepts		47.4%	3.9%
NARA-FS-05 King/Horse Cr Doug-fir / Cedar Fines	13.9%		NM
NARA-FS-06 Sisters OR Pine and Spruce Accepts		54.0%	7.7%
NARA-FS-06 Sisters OR Pine and Spruce Fines	24.5%		NM
NARA-FS-07 Alder - Hemlock Port Angeles, WA Accepts		NM	NM
NARA-FS-07 Alder - Hemlock Port Angeles, WA Fines	NM		
NARA-FS-08 Longview Alder / DFir Hog Fuel Accepts		59.9%	30.1%
NARA-FS-08 Longview Alder / DFir Hog Fuel Fines	33.6%		NM
NARA FS-10 Douglas-fir Forest Residual - Accepts		43.9%	3.4%
NARA FS-10 Douglas-fir Forest Residual - Fines	9.0%		NM
NARA FS-11 Douglas-fir Grinding Trials Composite Accepts	NA		NA
NARA FS-12 Douglas-fir Grinding Trials Tops & Limbs Accepts	6.22%	13.6%	10.1
NARA FS-13 Douglas-fir Grinding Trials Pulp Logs Accepts	4.83%	21.5%	2.5
NARA FS-14 Douglas-fir Grinding Trials Log Chunks Accepts	5.93%	21.3%	2.2
NARA FS-15 Fresh Douglas-fir Grinding Trials as-received		59.0%	NM
NARA FS-17 Siuslaw 900 Douglas-fir Residuals Accepts		44.7%	8.40
NARA FS-18 CSKT Montana Int D-fir and Pine FHR Accepts		38.2%	8.40
NARA FS-19 Muckleshoot Enumclaw WA FHR Accepts		31.0%	8.27
NARA FS-20 1,000 gal biojet feedstock blend Accepts		41.1%	8.27

[1] FS-16, Douglas-fir Land Clearing "Flinger" Trials, was a candidate for the 1,000 gallon biofuel production task but eventually was not used, so there is no test data for FS-16.

Table FS2-1.2. Summary chemical composition analysis of NARA feedstocks.

Summary Chemical Analyses NARA Feedstocks											
Feedstock	Total Polysaccharides	Hexose Polysaccharides	Pentose Polysaccharides	Ash-free Lignin, Acid-Insoluble (Klason)	Acid-soluble Lignin	Hot Water Extractives	Ethanol Extractives	Ash	Acetyl Groups	**Total**
NARA-FS-01 SW WA Douglas-fir Reference Wood Chips	63.51	59.4	4.10	25.93	1.69	5.64	0.50	0.09	1.64	**99.0**
NARA-FS-02 SW WA Hem/Spruce Forest Residuals Accepts	51.63	45.8	5.82	36.18	0.50	5.22	2.81	1.45	NM	**97.8**
NARA-FS-02 SW WA Hem/Spruce Forest Residuals Fines	32.97	28.9	4.08	37.43	0.87	6.92	4.93	10.48	NM	**93.6**
NARA-FS-03 NW OR Dfir Forest Residuals Accepts	58.28	50.80	7.47	29.96	2.57	4.91	0.97	0.91	1.73	**99.3**
NARA-FS-03 NW OR Dfir Forest Residuals Fines	35.10	30.4	4.73	31.97	0.74	5.55	4.01	15.27	NM	**92.6**
NARA-FS-04 N OR Coast Forest Residuals Accepts	48.55	43.0	5.59	33.55	0.63	4.91	3.09	2.37	NM	**93.1**
NARA-FS-04 N OR Coast Forest Residuals Fines	29.38	24.9	4.50	39.29	1.10	6.07	6.47	8.47		**90.8**
NARA-FS-05 King/Horse Cr Doug-fir / Cedar Accepts	56.56	49.8	6.72	27.62	0.43	5.11	2.49	1.65	NM	**93.9**
NARA-FS-05 King/Horse Cr Doug-fir / Cedar Fines	35.10	29.8	5.30	30.71	0.83	7.49	6.16	15.20	NM	**95.5**
NARA-FS-06 Sisters OR Pine and Spruce Accepts	46.45	37.6	8.89	31.81	0.58	5.43	5.11	2.82	NM	**92.2**
NARA-FS-06 Sisters OR Pine and Spruce Fines	30.12	23.7	6.42	35.39	0.84	7.08	6.29	12.70	NM	**92.4**
NARA-FS-07 Alder - Hemlock Port Angeles, WA Accepts	58.74	46.4	12.36	28.00	1.10	3.65	2.57	0.64	NM	**94.7**
NARA-FS-07 Alder - Hemlock Port Angeles, WA Fines	46.05	33.0	13.07	35.50	1.23	4.75	4.55	2.08	NM	**94.2**
NARA-FS-08 Longview Alder / DFir Hog Fuel Accepts	46.48	38.1	8.37	31.03	0.88	5.52	3.14	5.76	NM	**92.8**
NARA-FS-08 Longview Alder / DFir Hog Fuel Fines	44.10	32.8	11.28	31.95	1.20	5.79	2.48	8.92	NM	**94.4**
NARA FS-10 Douglas-fir Forest Residual - Accepts	57.89	52.80	5.10	27.04	1.96	6.10	0.63	0.12	1.76	**95.5**
NARA FS-10 Douglas-fir Forest Residual - Fines	50.60	44.9	5.66	30.66	0.56	4.34	4.33	1.97	NM	**92.5**
NARA FS-11 Douglas-fir Grinding Trials Composite Accepts	57.99	51.7	6.31	26.93	0.35	4.81	3.96	0.31	NM	**94.4**
NARA FS-12 Douglas-fir Grinding Trials Tops & Limbs Accepts	56.27	49.2	7.10	28.60	0.43	5.92	5.41	0.71	NM	**97.3**
NARA FS-13 Douglas-fir Grinding Trials Pulp Logs Accepts	61.79	55.6	6.22	26.80	0.37	3.77	2.59	0.24	NM	**95.6**
NARA FS-14 Douglas-fir Grinding Trials Log Chunks Accepts	61.74	57.4	4.30	27.23	0.27	3.89	3.71	0.16	NM	**97.0**
NARA FS-15 Fresh Douglas-fir Grinding Trials as-received	44.64	37.8	6.88	34.47	0.64	6.60	3.35	10.73	NM	**100.4**
NARA FS-15 Fresh Douglas-fir Grinding Trials Fines	Not measured									
NARA FS-16 Douglas-fir Land Clearing "Flinger" trials	Not tested									
NARA FS-17 Siuslaw 900 Douglas-fir Residuals Accepts	60.35	52.0	8.33	29.30	2.95	3.47	0.74	0.47	NM	**97.3**
NARA FS-18 CSKT Montana Int D-fir and Pine FHR Accepts	60.61	54.4	6.22	31.20	2.00	6.14	1.93	0.48	NM	**102.4**
NARA FS-19 Muckleshoot Enumclaw WA FHR Accepts	64.18	59.8	4.35	29.60	1.70	4.57	1.21	0.06	NM	**101.3**
NARA FS-20 1,000 gal biojet feedstock blend Accepts	59.69	52.2	7.53	30.20	3.00	2.43	0.94	0.60	NM	**96.9**

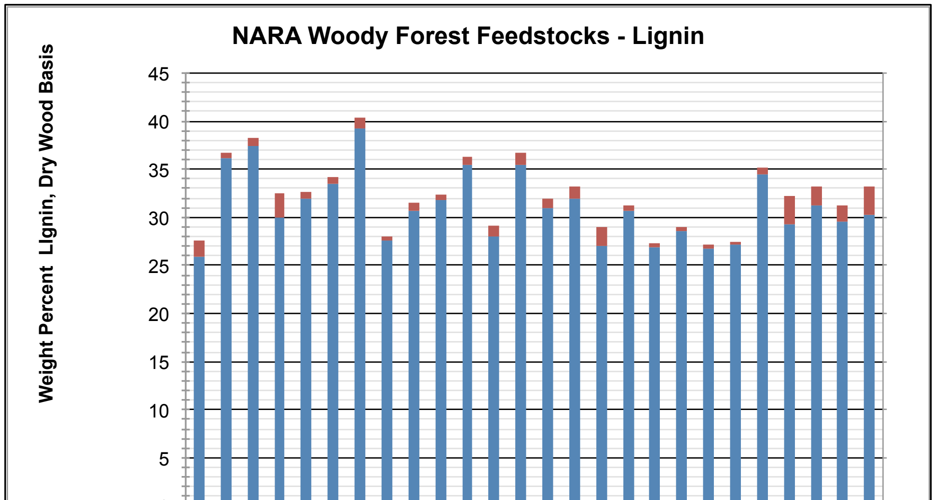


	FS-01 A	FS-02 A	FS-02 F	FS-03 A	FS-03 F	FS-04 A	FS-04 F	FS-05 A	FS-05 F	FS-06 A	FS-06 F	FS-07 A	FS-07 F	FS-08 A	FS-08 F	FS-10 A	FS-10 F	FS-11 A	FS-12 A	FS-13 A	FS-14 A	FS-15 AR	FS-17 A	FS-18 A	FS-19 A	FS-20 A
Mannan	11.85	8.19	4.80	8.95	5.06	7.86	4.57	9.97	5.38	6.25	4.15	4.87	2.77	5.46	2.84	10.10	9.07	10.20	8.46	11.17	12.60	6.09	8.48	11.20	12.30	9.14
Xylan	3.80	4.50	2.58	6.59	3.43	3.86	2.12	5.00	3.28	5.97	4.05	11.67	11.73	7.03	10.60	4.61	4.22	5.05	5.39	5.14	3.41	4.78	7.49	4.94	3.70	6.55
Glucan	45.27	32.57	21.33	38.12	22.67	30.90	17.93	36.77	21.90	27.17	17.03	39.97	28.77	30.90	28.83	40.30	33.03	37.93	36.43	41.30	41.80	27.13	40.67	40.00	45.30	39.80
Galactan	2.28	5.05	2.76	3.73	2.64	4.20	2.38	3.10	2.52	4.14	2.52	1.54	1.45	1.75	1.15	2.39	2.84	3.54	4.28	3.10	3.04	4.54	2.88	3.19	2.23	3.22
Arabinan	0.30	1.31	1.50	0.88	1.30	1.73	2.38	1.72	2.02	2.92	2.37	0.70	1.33	1.34	0.68	0.49	1.44	1.26	1.71	1.08	0.89	2.10	0.84	1.28	0.65	0.98
Total	63.5	51.6	33.0	58.3	35.1	48.6	29.4	56.6	35.1	46.5	30.1	58.7	46.1	46.5	44.1	57.9	50.6	58.0	56.3	61.8	61.7	44.6	60.35	60.61	64.18	59.69

Feedstock

NARA Feedstocks Tracking.xlsx / Poly8 Marrs

Figure FS2-1.1. Polysaccharides in NARA Feedstock samples



	FS-01 A	FS-02 A	FS-02 F	FS-03 A	FS-03 F	FS-04 A	FS-04 F	FS-05 A	FS-05 F	FS-06 A	FS-06 F	FS-07 A	FS-07 F	FS-08 A	FS-08 F	FS-10 A	FS-10 F	FS-11 A	FS-12 A	FS-13 A	FS-14 A	FS-15 AR	FS-17 A	FS-18 A	FS-19 A	FS-20 A
Acid-soluble Lignin	1.69	0.50	0.87	2.57	0.74	0.63	1.10	0.43	0.83	0.58	0.84	1.10	1.23	0.88	1.20	1.96	0.56	0.35	0.43	0.37	0.27	0.64	2.95	2.00	1.70	3.00
Ash-free Lignin, Acid-Insoluble (Klason)	25.93	36.18	37.43	29.96	31.97	33.55	39.29	27.62	30.71	31.81	35.39	28.00	35.50	31.03	31.95	27.04	30.66	26.93	28.60	26.80	27.23	34.47	29.30	31.20	29.60	30.20
Total Lignin	27.62	36.67	38.30	32.54	32.71	34.17	40.39	28.05	31.54	32.39	36.23	29.10	36.73	31.91	33.15	29.00	31.22	27.29	29.03	27.17	27.51	35.11	32.25	33.20	31.30	33.20

Feedstock

NARA Feedstocks Tracking.xlsx / Lignin xlc Marrs

Figure FS2-1.2. Acid-Insoluble and Acid-soluble lignin in NARA feedstock samples.

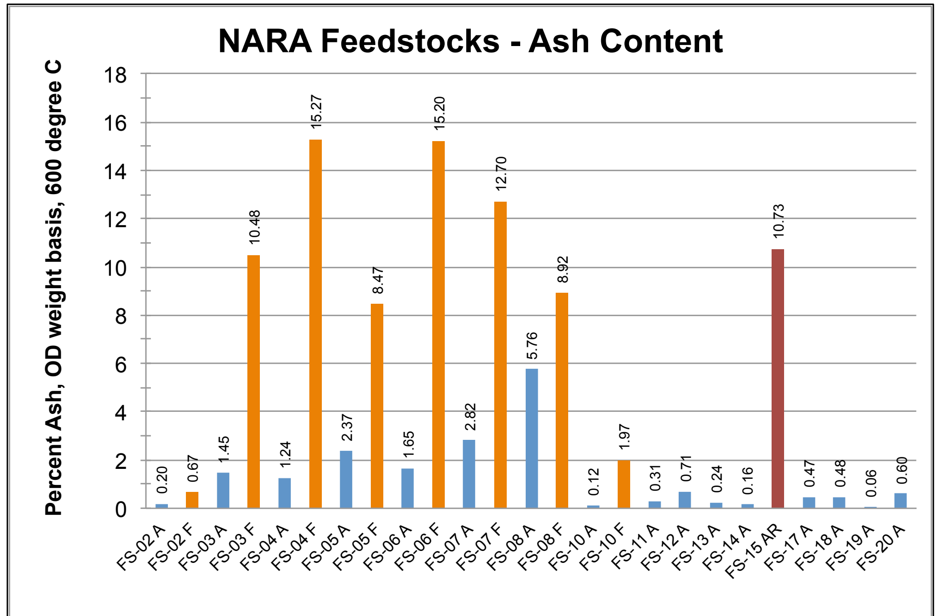
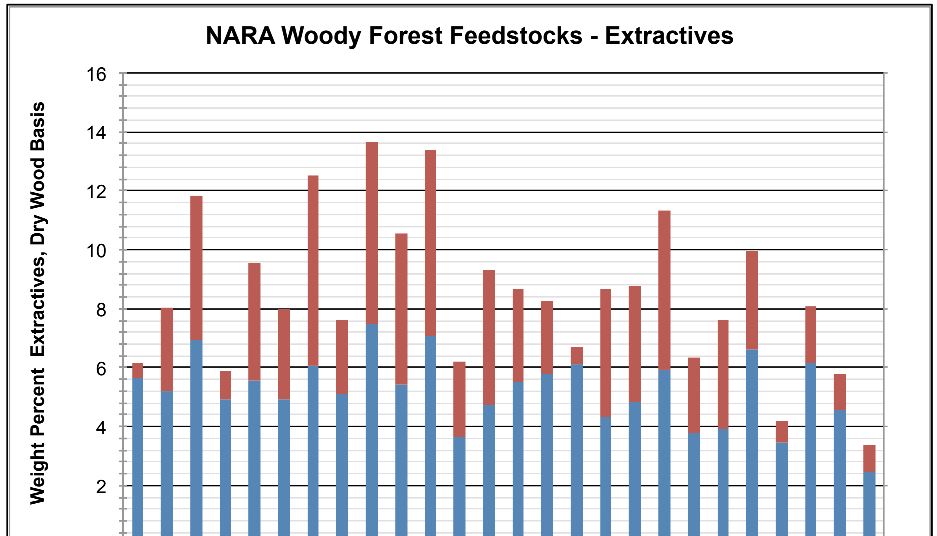


Figure FS2-1.3. Ash content (600 degree C) in NARA feedstock samples.



	FS-01 A	FS-02 A	FS-02 F	FS-03 A	FS-03 F	FS-04 A	FS-04 F	FS-05 A	FS-05 F	FS-06 A	FS-06 F	FS-07 A	FS-07 F	FS-08 A	FS-08 F	FS-10 A	FS-10 F	FS-11 A	FS-12 A	FS-13 A	FS-14 A	FS-15 AR	FS-17 A	FS-18 A	FS-19 A	FS-20 A
Ethanol Extractives	0.50	2.81	4.93	0.97	4.01	3.09	6.47	2.49	6.16	5.11	6.29	2.57	4.55	3.14	2.48	0.63	4.33	3.96	5.41	2.59	3.71	3.35	0.74	1.93	1.21	0.94
Hot Water Extractives	5.64	5.22	6.92	4.91	5.55	4.91	6.07	5.11	7.49	5.43	7.08	3.65	4.75	5.52	5.79	6.10	4.34	4.81	5.92	3.77	3.89	6.60	3.47	6.14	4.57	2.43
Total Extractives	6.14	8.03	11.85	5.88	9.56	8.00	12.54	7.61	13.65	10.54	13.37	6.23	9.30	8.67	8.27	6.73	8.67	8.78	11.33	6.36	7.60	9.95	4.21	8.07	5.78	3.37

Feedstock

NARA Feedstocks Tracking.xlsx / Extractives xlc Marrs

Figure FS2-1.4. Extractives content in NARA feedstock samples.

Conclusions/Discussion

From the NARA project outset, one boundary condition was to produce bio-based jet fuel (or IPK) from softwood as at least one main product. The IPK is produced from IBA, which is produced from fermentation of wood sugar monomers, which are produced from the hydrolysis of the wood polysaccharides. Thus, it is logically connected that the polysaccharides content of the feedstock will have a positive correlation to the eventual total IPK yield on wood, and thus overall project economics. Additionally it was known that the major non-wood component of FHR would be the bark content, and bark has a relatively lower polysaccharide content compared to wood. Considerable attention was paid to the variation of polysaccharides and bark content in the first 10 NARA samples.

However as the NARA project evolved and high-value co-products from the lignin-rich residues were identified, the overall process economics became buffered against changes in the largest feedstock components—polysaccharides and lignin. That is, samples with more lignin (and extractives) were correlated with less polysaccharide content. What was lost in production of IPK from sugars was offset by more lignin-rich residue left after alcohol-to-jet (ATJ), thus increasing the activated carbon (AC) production. Since the total revenue from these two streams is similar in magnitude in the base case, the net impact on economics is moderated.

For the benefit of future providers and users of FHR feedstocks, the following comments summarize the general nature of variations in key characteristics and how they would tend to influence project economics (that is, how important will it be to set feedstock specifications around these characteristics).

Moisture content

Moisture content of FHR varies considerably because residuals are left for widely varying periods of time (days to years) from timber harvest to residuals harvest, and likely to a smaller extent the season of year when the FHR is harvested (see Table FS2-1.1). Material harvested soon after the timber harvest, like FS-15, Fresh Grinding Trials, had a very high moisture content of 59% wet basis moisture. The other FHR samples were at varying moisture contents, down to a low measured on FS-03 of 38%. It is expected that average moisture to a conversion facility will be about 45%, but this will vary considerably between each truckload. Fortunately the NARA conversion process is a "wet" process where the pretreatment actually adds water (in the pretreatment liquor) up to 4:1 liquor-to-wood ratio, so these variations in moisture content are not of great concern to the process per se. However, sample FS-15 did show a correlation of high moisture with very high ash content (see Figure FS2-1.3). Sample FS-15 did *not* have the fines screened out before testing, and the ~10% ash in the total sample would be much higher than the weighted average for other samples. It is believed that this is due to inorganic contamination from soils during harvesting of the very fresh material. It is unclear whether and how fresh material can be harvested without such high levels of contamination, but that would *likely* be required.

Ash content

Ash content measures the inorganic components in a feedstock, and clean wood has quite low ash content. For example, FS-01 Douglas-fir pulp chips with low bark have only 0.09% ash. Ash content is often monitored, and specifications for levels are used to control ash buildup in combustion of FHR. Specifications for ash in FHR for energy are in the 1.5 to 2% range (Lane Forest Products – personal communications). If care is not exercised in accumulating residuals into piles on a site, and / or the loader to the grinder is not careful to avoid loading contaminated materials, the ash content can readily exceed specifications. While the NARA process is not commercialized so no specific ash content limit is set, it seems likely that something in the range of 2 to 3% would be a reasonable (and achievable) ash specification. A main goal of the mill-simulated fines screening is to remove a portion of the feedstock most contaminated with inorganic materials. Figure FS2-1.3 shows the resulting ash content of screen accepts and fines for the various NARA feedstocks tested. It can be seen that the accepts of most would achieve the 2-3% specification, whereas the fines have, for the most part, very elevated levels, likely warranting the proposed removal from the conversion stream.

Species content

As noted previously, the species that are left as residue following a commercial softwood timber harvest can vary widely by both the geographic source as well as the amount of non-commercial species (minor softwoods or hardwoods) present on the tract. Table FS2-1.3 shows the species content of screened accepts samples with those species present in amounts greater than 5% indicated by colored cells. There is obviously quite a range of softwood species in the materials sampled, and often non-trivial amounts of hardwoods. None of these species mixes are known to have properties that would have significant effects on the pretreatment, fermentation, or oligimerization steps in the NARA process, aside from the polysaccharides content affecting the IPK net yield through the process. As noted, since the final base case derives revenue from both sugars and lignin, the species mix is not likely to have significant effect on overall economics. In other words, for both provider and user of feedstock the best option is to harvest as much biomass as can be economically gathered (to keep feedstock costs as low as possible) without regard to species (don't waste time sorting and reduce overall production).

Due to the difficulty and expense of testing a specific feedstock through all the NARA process stages, only samples FS-01, FS-03 and FS-10 were tested extensively and of these FS-03 and FS-10 form the basis for all underlying yield assumptions, etc. that are underpinnings of the NARA TEA (Marrs and Spink, 2016). The blend created for the 1,000 gallon bio-jet production task (Wooley et al, 2016) was of course processed at considerable scale (compared to lab tests) and since it was targeted, and achieved a very similar composition to FS-10, our confidence in the feasibility of the assumed process in the TEA is bolstered.

Variations in key chemical constituents: polysaccharides, lignin and extractives
While there is considerable relative variation in key properties, there are also correlations between them. Figure FS2-1.5 shows the correlation between polysaccharides and lignin content. Polysaccharides are by far the largest chemical constituent, and lignin the second, and to a fair extent increases in one are offset by decreases in the other (although not at a 1:1 rate, as shown by the slope coefficient of -0.26).

Table FS2-1.3. Species mix in NARA samples (by microscopic fiber identification).

Species mix by microscopic visual measurement of fiberized samples, weight percent							> 5%	
Feedstock	**Douglas fir**	**Hemlock**	**Cedar**	**Pine**	**Spruce**	**True fir**	**Hardwood**	**Non-woody**
NARA-FS-01 SW WA Douglas-fir Reference Wood Chips	**91**	**5**	**0**	**1**	**3**	**0**	**0**	
				lodgepole				
NARA-FS-02 SW WA Hem/Spruce Forest Residuals Accepts								
				lodgepole			maple, ash	
NARA-FS-03 NW OR Dfir Forest Residuals Accepts	87	2	1	2	2	0	6	
				lodgepole			maple, beech, ash	
NARA-FS-04 N OR Coast Forest Residuals Accepts								
NARA-FS-05 King/Horse Cr Doug-fir / Cedar Accepts	86	4	7	0	2	0	1	
							alder	
NARA-FS-06 Sisters OR Pine and Spruce Accepts	0	3		88	7	0	0	2
								grass
NARA-FS-07 Port Angeles WA alder-hemlock	0	42	1	trace	10	0	47	
							alder	
NARA-FS-08 Longview Alder / DFir Hog Fuel Accepts	27	10	1	4	2	0	56	
							alder	
NARA FS-10 Douglas-fir Forest Residual - Accepts	64	15	1	1	3	1	15	
				lodgepole or ponderosa			maple	
NARA FS-11 Douglas-fir Grinding Trials Composite as-received	66	4	0	2	1	0	27	
				lodgepole or ponderosa			maple, ash	
NARA FS-12 Douglas-fir Grinding Trials Tops & Limbs as-received	92	1	1	0	1	0	5	
NARA FS-13 Douglas-fir Grinding Trials Pulp Logs as-received	86	4	0	0	2	0	8	
NARA FS-14 Douglas-fir Grinding Trials Log Chunks as-received	90	8	0	0	2	0	0	
NARA FS-15 Fresh Douglas-fir Grinding Trials Accepts	93	2	0	1	1	0	3	
NARA FS-16 Douglas-fir Land Clearing "Flinger" trials	not tested							
NARA FS-17 Siuslaw 900 Douglas-fir Residuals	64	9	1	3	3	1	19	
NARA FS-18 CSKT Montana Int D-fir and Pine FHR	97	1	0	0	1	0	1	
NARA FS-19 Muckleshoot Enumclaw WA FHR	97	1	0	1	1	0	0	
NARA FS-20 1,000 gal biojet feedstock blend	68	5	1	3	4	0	19	

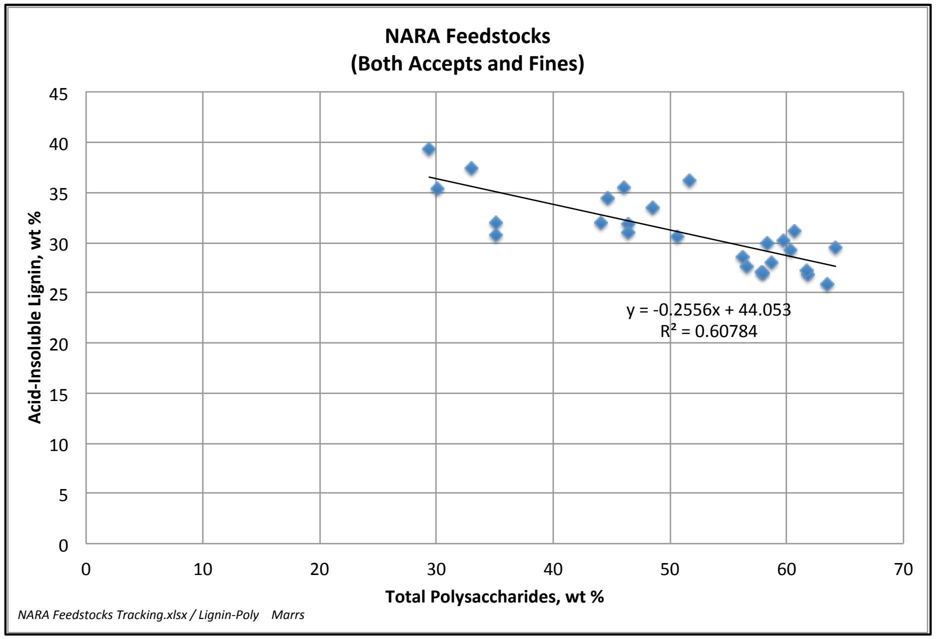


Figure FS2-1.5. Relationship between polysaccharides and lignin content.

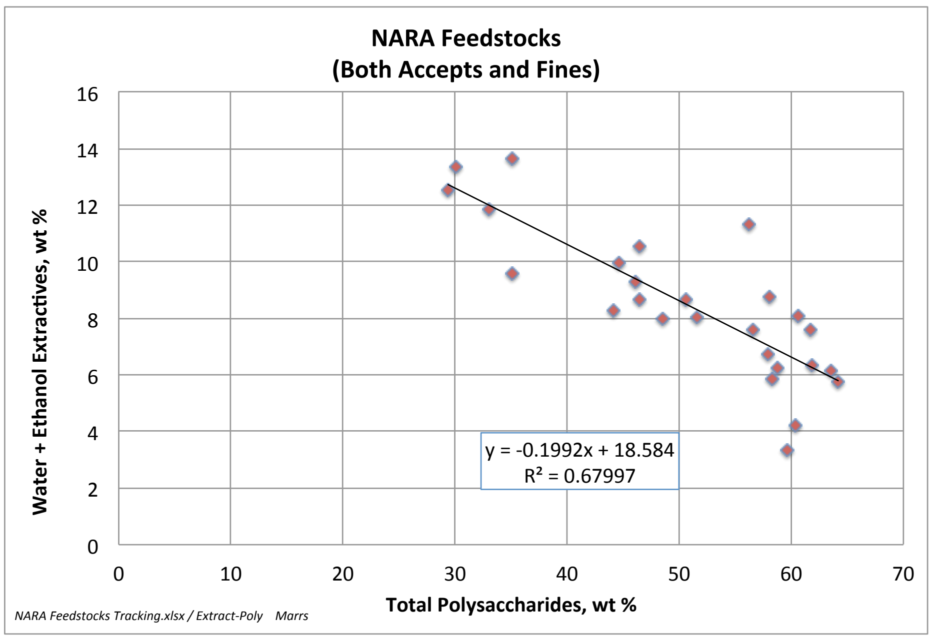


Figure FS2-1.6. Extractives are negatively correlated with polysaccharides content in the NARA FHR feedstock samples.

To a fair extent, since the analysis of FHR composition is relative, when one major component increases (like polysaccharides), numerically other components must decrease (Figure FS2-1.6). Since lignin and extractives are the next two largest component, and both are negatively correlated with polysaccharides, *and* the fact that neither lignin nor extractives contribute to IPK production, but both contribute to LS and AC production, we can assess the sum of those two components. Figure FS2-1.7 shows that when lignin and extractives are correlated with polysaccharides, the (negative) correlation becomes even stronger ($r^2 = 0.79$).

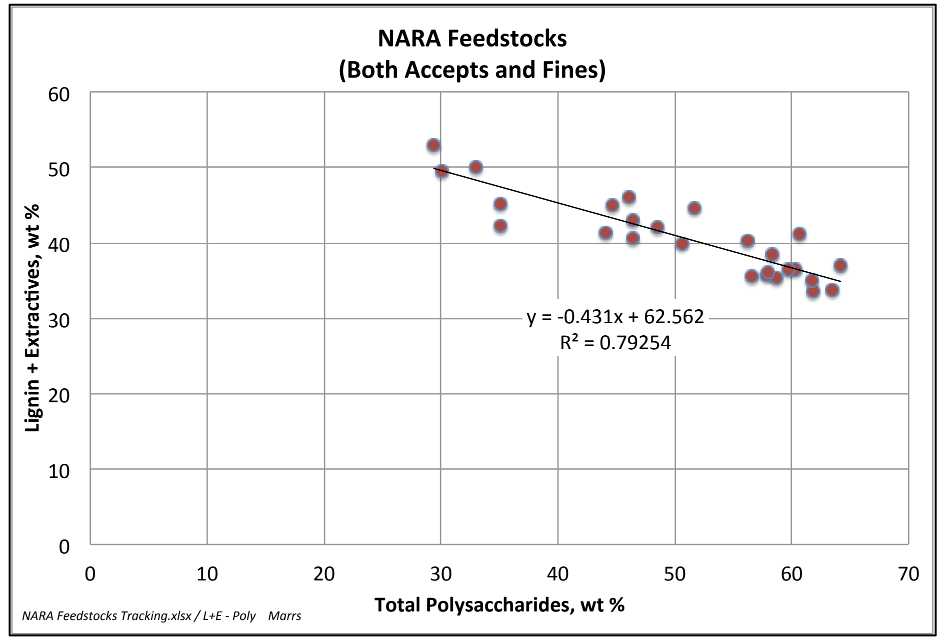


Figure FS2-1.7. Polysaccharide content is negatively correlated with the sum of lignin plus extractives.

Bark and screen fines content

Figure FS2-1.8 shows the levels of two important characteristics of bio-fuel feedstocks for conversion via fermentation of sugars—total polysaccharides content and bark content. Additionally, since bark has a tendency to pulverize to finer material upon grinding, there is often an impact on total screen fines and the bark content. The screen fines levels impact overall conversion economics, as they only have energy value and do not get converted to the primary conversion product of IPK. Screen fines reject levels are shown in Figure FS2-1.9 for each feedstock with measured bark content remaining in the accepts.

Examination of Figure FS2-1.8 shows the general pattern of expectation—that samples with higher bark content (FHR and hog fuel in particular) have lower polysaccharides content. The “cleanest” material, the Douglas-fir pulp chips FS-01, has

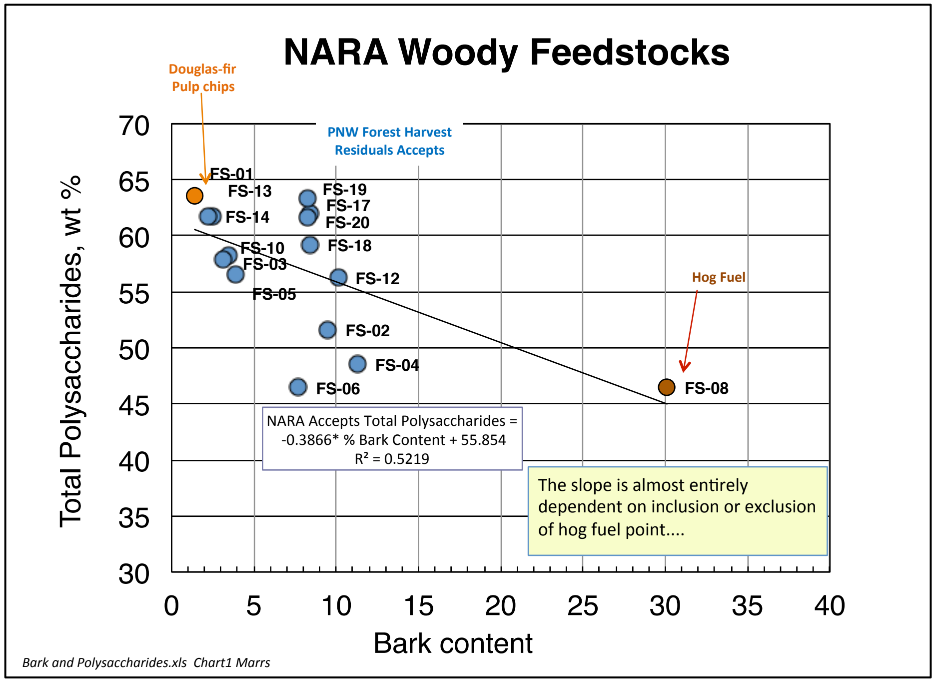


Figure FS2-1.8. Broadly speaking, much of the variation in polysaccharides content is related to the bark content of the feedstock

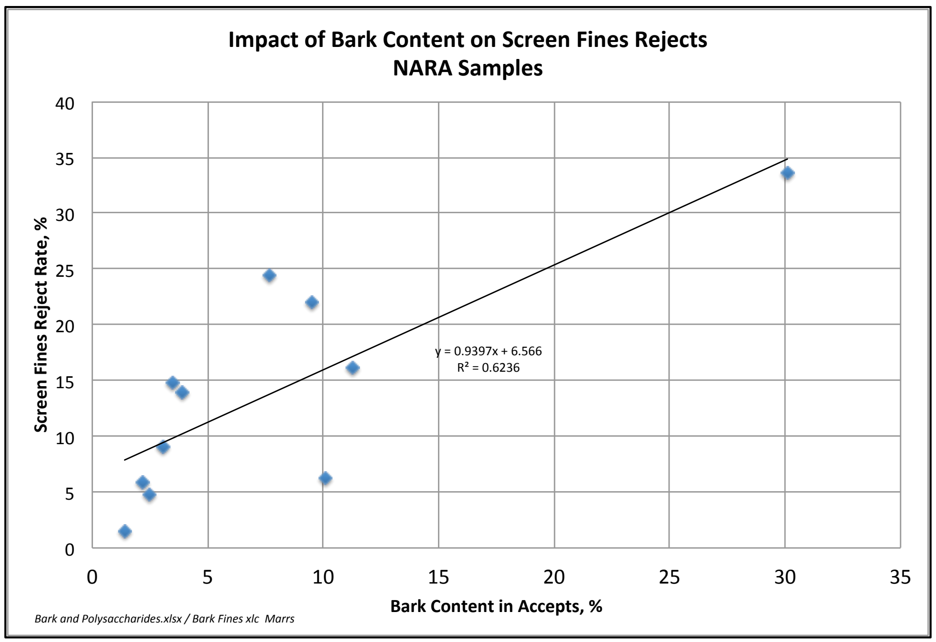


Figure FS2-1.9. Screen fines reject rates tend to be higher with higher bark content.

about the highest level of polysaccharides. For most of the materials shown there is a paired screen fines composition test which shows the substantially reduced polysaccharides in fines. While bark content cannot be visually determined for fines, it is likely that this is the main underlying cause for lower polysaccharides in fines.

Conclusion and summary for forest harvest residuals as feedstock

While FHR have been shown to be quite variable in key properties (polysaccharides, lignin, extractives, ash, moisture, species, particle sizes), tests of key FHR types (FS-03 and FS-10), with comparison to "clean" Douglas-fir pulp chips (FS-01) showed no inhibitory effects that would impact IBA yield during the processing from pretreatment, hydrolysis, and fermentation. The complexity, and thus time and cost, to test any one feedstock through the entire mild bisulfite pretreatment, enzymatic hydrolysis, and fermentation to isobutanol precludes testing of every feedstock. Instead, the only economically practical method is to make inferences based upon chemical composition and evaluation of these impacts (yield, etc.) in the TEA. Since the NARA TEA (Marrs, Spink & Gao, 2016) identified that we need significant additional revenue from lignin-based co-products to be economically viable, yield changes to IPK have reduced impact on total return when the material NOT going to IPK instead goes to the lignin co-product, and total revenue remains similar. We have demonstrated that the type of FHR feedstock present in the greatest amounts in the NARA region—FHR from commercial Douglas-fir timber harvest—can be successfully processed into bio-jet in the NARA process, and furthermore, the variability in species composition and components (bark, wood) are not likely to be significant barriers to use of these feedstocks in a NARA process.

TASK 2: SPECIFICATIONS FOR FOREST HARVEST RESIDUALS AS FEEDSTOCK

Background

One of the earliest questions asked by the NARA Feedstock Logistics team members was to the conversion partners, asking "What feedstock specifications do you have (or need)?". In return the NARA Conversion team members asked the Feedstocks team "What choices do you have available?".

The boundary conditions for NARA feedstocks from the project outset have included that the feedstock be comprised of softwoods from the Pacific Northwest. Our sampling of potential feedstocks to answer the second question above included "clean" Douglas-fir pulp chips, "dirty" hog fuel from a softwood pulp mill, and a set of Forest Harvest Residuals (FHR) ranging over various conditions in western WA and OR.

Early in the NARA project, the cost and availability structure of these three candidate classes (pulp chips, hog fuel or FHR) the FHR category was deemed the most plausible given likely chemical composition, projected price, and availability at scale.

For many project years, the NARA base case feedstock has been FS-10, considered typical of a large segment of available FHR – residuals left after commercial timber harvest from a predominantly Douglas-fir timber stand. Virtually all technical details underpinning the NATA TEA (Marrs & Spink, 2016) have been done via lab work on FS-10 (MBS pretreatment, enzymatic hydrolysis, fermentation to IBA, preparation of activated carbon, ASPEN mass and energy balance, etc.), and thus the TEA assumes an FS-10-like composition.

What has been lacking so far is a linkage between feedstock options as defined by NARA characterization tests and an economic impact on the overall process, including an understanding of *why* this occurs. This connection would shed light on defining what feedstock specifications *could* or *should* be, both from a producer and conversion (buyer's) points of view.

It is clearly not within the time or cost scope of the NARA project to actually take samples of varying feedstocks through all process conversion steps, create ASPEN mass and energy flows, and modify the base case TEA to show explicitly the estimated economic impact. However, a simplified approach, which approximates the net effect for a limited subset of extremes in the feedstocks, should be feasible and useful. Such an evaluation is presented here.

Approach

First, our belief (assumption) is that moisture content (between about 50% and 15% moisture, wet weight basis) and species (within the ranges found in softwood timber harvest residuals) have little impact on the process or economics. We are taking the chemical composition of three extreme potential feedstocks (pulp chips, hog fuel and DF FHR) to represent the full range of how much variation we might expect (or have available to the IBR if we so choose). Primary chemical constituents (polysaccharides, lignin, extractives, ash) will be translated through yield stages in the process to final selling products (IPK, LS, AC) based upon best available rationale. Changes in output product amounts, at the same selling price as the base case, will lead to different income streams for different cases.

On the cost side, the largest difference would be the expected purchase price difference of those three feedstocks (based mostly on market demand for each type). Market data will be used for pulp chips ($125/BDT) and hog fuel ($45/BDT), and the NARA estimate for FHR ($62.60/BDT). While changes in composition would actually change internal IBR mass flows somewhat, and thus equipment sizes and operating costs, for this work we are assuming these are second-order effects and will be ignored in this approximation. One slight difficulty to overcome is that the analytical test procedures did not account for 100% of the tested material, and for some samples this was never fully resolved (for example, FS-10 analytical tests only sum to 95.5%). For this exercise we will simply pro-rate the measured proportions for FS-10 to 100%, as if all components were mis-measured proportionately.

Note that we assume each potential feedstock will be screened to remove fines, and thus the analytical test results used are for the accepts portion only—that portion being sent to conversion. Also, since the amount of material screened out varies by feedstock, we adjust the cost basis to the conversion mouth by downgrading all fines removed to hog fuel value ($45/BDT). Table FS2-2.1 shows the purchase price, screen fines reject rates, and resulting cost to conversion mouth for the net 777k BDT/yr to the IBR. Note that pulp chip cost is raised very little over purchase price because there are few fines. Hog fuel has no increase in cost because it was purchased at hog fuel price, and fines are sent to hog fuel. FHR FS-10 is intermediate, taking a downgrade of about $17/BDT for the portion sent to fines—but only 9% of the material is sent to fines, resulting in a couple dollars per ton cost increase in accepts sent to conversion.

Table FS2-2.1. Impact of screen fines on cost to conversion mouth.

	FS-01 DF Pulp Chip Accepts	FS-10 DF FHR Accepts	FS-08 Hog Fuel Accepts
Purchase price at gate, $/BDT	$125	$62.60	$45
Screen Fines percent rejected to Hog Fuel	1.50%	9.00%	59.90%
Value of screen fines as hog fuel, $/BDT	$45	$45	$45
Cost basis to IBR, $/BDT	**$126.20**	**$64.18**	**$45.00**

Results

The compositions of the three feedstocks of interest, with groupings by major components, are shown in Table FS2-2.2 and Figure FS2-2.1.

Table FS2-2.2. Composition of three feedstock choices for NARA, pro-rated to account for 100% of the material.

Pro-rated to 100%	FS-01 DF Pulp Chips	FS-10 DF FHR	FS-08 Hog Fuel Accepts
Polysaccharides (Sugars	64.14	60.61	50.08
Lignin	27.90	30.36	34.38
Extractives	6.20	7.04	9.34
Acetyl groups	1.66	1.85	0.00
Ash	0.09	0.13	6.20
Total	100.00	100.00	100.00

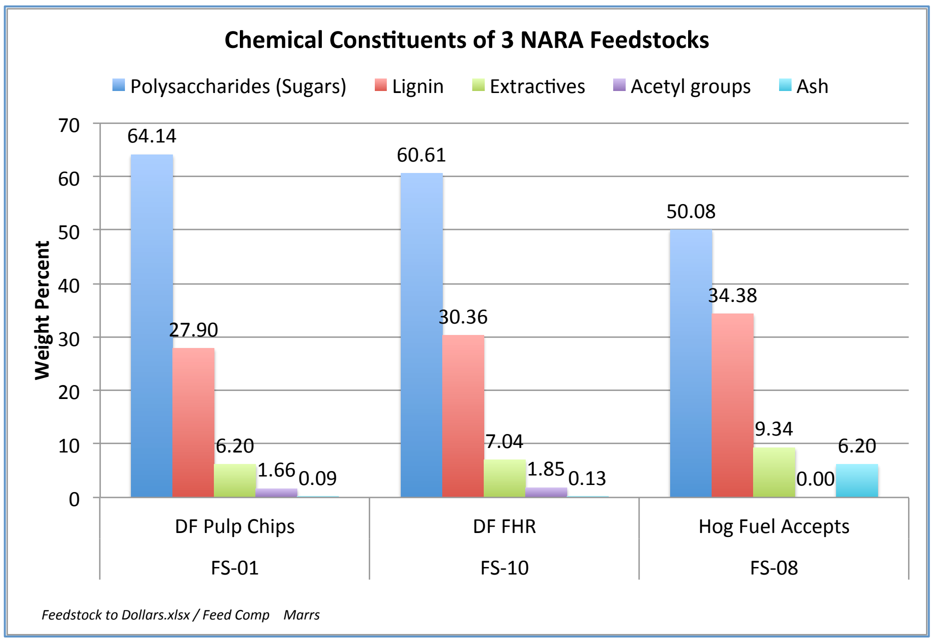


Figure FS2-2.1. Chemical constituents (adjusted proportionately to total 100%).

Examination of the bark content and species for these samples supports the premise that very little of the composition difference arises from species differences—instead the main source of chemical variation is the varying quantities of bark present. Douglas-fir bark has lower polysaccharides and higher lignin and extractives, and to a large extent accounts for the net chemical composition differences in the accepts fed to conversion. This observation is supported by data from Zhang et al. 2012, where they measured pure wood and bark separated from NARA Douglas-fir FHR sample. Extracted data from their publication shows total polysaccharides for the wood component to be 62%, while the bark component had only 35%. The bulk of the difference was due to the much higher lignin content of the bark (extractives were not reported explicitly, but are noted as being higher in bark). Robinson et al., 2002, also reported measurements of pure Douglas-fir wood and bark—he reports total polysaccharides in wood as 67% and bark as 22%, giving similar results to Zhang et al., 2012. Figure FS2-2.2 shows the NARA feedstock mixtures with the pure wood and bark reference values, suggesting that empirically, bark content is a principle determinant of total polysaccharides content of a mixture.

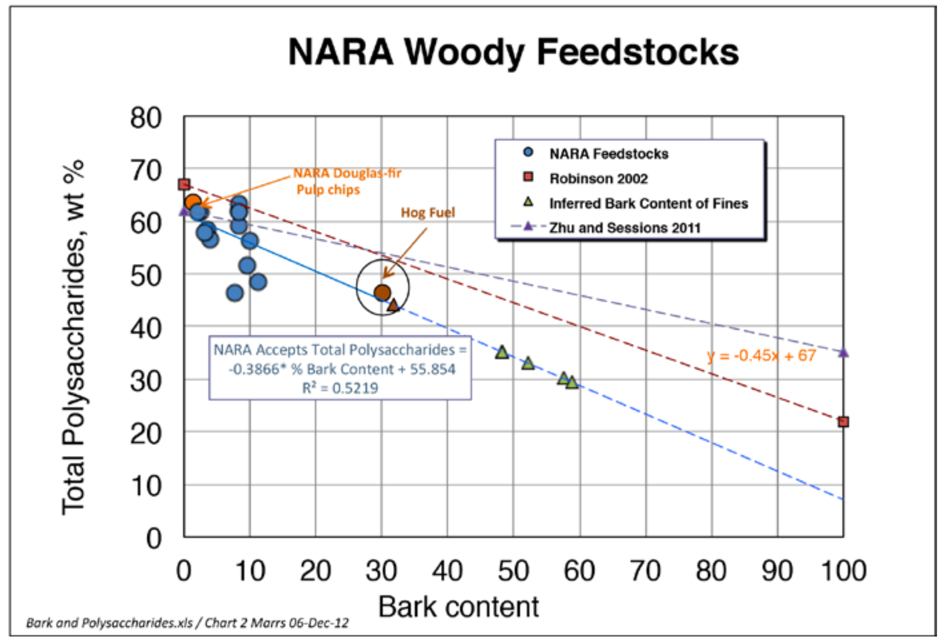


Figure FS2-2.2. Relationship between bark and polysaccharides content for NARA samples and pure wood and bark.

Key assumptions linking FS components to final products and economic impact

Polysaccharides to IPK – key assumptions

Assume that all incoming wood polysaccharides (roughly 60% of the feedstock mass) are either dissolved in spent sulfite liquor (SSL) as monomers, or they stay in the pretreatment solids (i.e., "pulp") to go through enzymatic hydrolysis to monomers. By either route, the sugar monomers are fermented to isobutanol (IBA) and combined following separation of IBA and sent on to production of isoparaffinic kerosene (IPK). In this work we use the yield of IPK based upon starting polysaccharides for the FS-10 base case to directly adjust IPK annual production for the different feedstocks. This is equivalent to assuming that every yield stage in the IPK process stays relatively the same and only incoming polysaccharides levels alter final amount of IPK. The assumptions are that only polysaccharides contribute to IBA and thus IPK (which is reasonable) and that all polysaccharides in alternate feedstocks contribute at the same rate as FS-10. This second assumption is not quite as plausible, as the ratio of pentoses and hexoses *would* affect fermentation results differently. Still, for approximation we will use that assumption. Table FS2-2.3 shows the projected amounts and resulting income from IPK for the three comparison feedstocks. Note that the methodology used is that the base case FS-10 produces 46.41 gallons IPK for each BDT FS-10 to conversion, so combined with the two assumptions above this is equivalent to 76.59 gallons IPK per BDT polysaccharides when there is 60% polysaccharides in the feedstock.

Polysaccharides to IPK - results

The revenue assumed for IPK in the NARA TEA (Marrs & Spink, 2016) can be either of two cases. In the "projected pricing" scenario, using EIA projected petro-jet as price basis for IPK ($2.56/gal IPK), and projected RINs value as the bio-fuel premium ($2.46/gal IPK), total revenue per gallon is $5.02/gal IPK (we'll refer to this as market pricing, or "MKT"). However since this MKT case does not appear economically viable (only 3.6% IRR), it would not likely be implemented, thus feedstock specs are moot (other than to show that even the best feedstock for MKT IPK does not bring the project into reasonable IRR). Therefore an alternative case is also reported for the NARA TEA, the so-called Miniumum Selling Price (MSP) case, where *some* source of bio-fuel premium is assumed in order to bring the project to 10% IRR so that there is some chance it would be commercialized. That case requires total MSP IPK revenue to be $7.31/gal IPK (roughly 50% higher than the MKT case), and changes in feedstock composition at that IRR level have more economic impact. Both are shown in Table FS2-2.3 for comparison, but one should focus on the MSP case as that is more likely if and when this process becomes economically viable.

Table FS2-2.3. IPK Production and Revenue for different feedstocks – IPK only production.

IPK Amount and Revenue			
	FS-01	**FS-10**	**FS-08**
	DF Pulp Chip Accepts	**DF FHR Accepts**	**Hog Fuel Accepts**
Polysaccharides (Sugars) weight percent	64.1	60.6	50.1
Annual k BDT Polysacc input to conversion	495,013	467,791	386,463
IPK MM Annual Gallons	37.90	35.82	29.59
Annual MM$ Revenue IPK @$5.02/gal ("MKT")	$190	$180	$149
Annual revenue change from MKT base, $MM	$10	$0	-$31
Percent change against FS-10 case revenue	6%	0%	-17%
Project V13.43 IRR if *only* this changed	4.55%	3.56%	0.52%
Annual MM$ Revenue IPK @$7.31 MSP	$277	$262	$216
Annual MSP revenue change from base, $MM	$15	$0	-$46
Project V13.43 MSP IRR if *only* this changed	11.03%	10.00%	6.69%
Assumed Feedstock Price to conversion	$126.20	$64.18	$45.00
V 13.43 MSP IRR with that FS price	**7.32%**	**10.00%**	**7.84%**

This shows that even though "higher-quality" pulp chips would give more IPK, and in the IPK-only production case probably give more total project revenue, the much higher cost of pulp chips would offset this IPK yield advantage and net a lower IRR than the base case FHR. Hog Fuel, conversely, even with a considerably lower price, has an IPK yield so low that again the IRR is less than for FHR. From this analysis one can conclude that *both* the pulp chips and the hog fuel are economically inferior to the FHR. This suggests that the initial NARA project assumptions were correct – that is—FHR is the best balance of quality and price (of these three options, at least) for IPK production alone. However, in the NARA TEA much of the income derives from co-products from the lignin-rich fraction not used in IPK production. The financial picture for the feedstock options could be different when we consider that a large portion of the feedstock material that doesn't go to IPK does go to other valuable co-products.

Lignin to co-products - assumptions

The next largest feedstock component after polysaccharides is the lignin, at roughly 30% for FHR. In the simplified approach used here, we assume that no lignin is utilized in the route of IBA to IPK (which is reasonable—the organisms only ferment sugars). The lignin (roughly 30% of the feedstock mass) is split into two fractions during pretreatment with mild bisulfite (MBS). The first is that portion which is soluble in cooking liquor and is dissolved in the spent sulfite liquor (SSL) as lignosulfonate compounds. These compounds (along with a good portion of the cooking chemicals) comprise the "lignosulfonate" (LS) sold as one of the IBR co-products. The second fraction is the insoluble portion of the lignin that stays with the pretreated pulp and goes to enzymatic hydrolysis, and fermentation, and alcohol-to-jet process, where we assume none of the lignin goes to IPK, nor to the atmosphere (as CO_2). Therefore all the weight of insoluble lignin ends up at the activated carbon (AC) production department (along with dead yeast cell bodies from fermentation of both SSL and hydrolyzed pulp)—i.e. "stillage". In AC production, a percentage (~20%) of the incoming stillage weight ends up in the AC product—the remainder going as volatile gases to the boiler or to vent gases. Based upon the ASPEN flows for lignin in pretreatment (which in turn are based upon laboratory MBS pretreatment results), about 23% of the lignin is dissolved in the SSL—the remaining 77% goes with the pulp.

For lignin we will use a similar approach to that for polysaccharides above—that is, we assume that if lignin to the conversion mouth increases by a certain amount, then the LS and AC both change proportionally compared to the base case FS-10 level. That is, the *portion* of the incoming lignin dissolved in MBS and insoluble going to AC production remains the same as for FS-10 FHR. We assume co-product *quality* does not change, thus the assumed unit selling prices for LS and AC stay constant, only the *amount* changes, thus revenue changes.

Extractives to co-products – assumptions

Before showing results of lignin changes due to feedstock choice, we will discuss the assumptions about extractives (about 7% of the feedstock mass) because, as will be seen, they are similar to lignin assumptions and thus we believe can be treated the same, and the two components effects calculated together.

There are two types of extractives measured analytically—water soluble and ethanol soluble. It is reasonable to assume that all of the water soluble extractives are dissolved into the SSL, along with some of the ethanol extractives, and the remaining ethanol extractives stay with the pretreated pulp. According to the ASPEN mass balance assumptions, 88% of the *total*[2] extractives weight goes with the SSL stream. None of the extractives in either of these flows (SSL or pulp) are fermentable thus contribute nothing to IBA->IPK nor CO_2 to the atmosphere during fermentation of sugars. Some of the volatile components *may* be lost during distillation and / or AC production, however these are relatively small amounts so are ignored in this analysis.

Thus, just like for lignin, we assume that the soluble portion of the extractives (88%) ends up in LS weight, and the insoluble portion goes to AC production, to have the same 18.8% yield on input to AC to be sold as the rest of the fermentation residual solids (FRS). Therefore we can simply add together 88% of the *difference* in feedstock extractives and 23% of the *difference* in feedstock lignin to get the mass flow *change* to LS from the base case. In the product sold as LS there are still some unfermented sugars and cooking chemicals, thus only about half the weight sold arises from the lignin and extractives, so this cuts the change in LS sold to half the impact of the (soluble lignin + soluble extractives) feedstock change.

For the insoluble portions of lignin and extractives we assume that 12% of the extractives plus 77% of the lignin goes to AC production in the FRS, with an 18.8% yield to AC product.

Lignin and Extractives ("L+E") to Lignosulfonates – results

Table FS2-2.4 shows the calculations and results of amount of change to LS sold per year due to changing lignin and extractives ("L+E") content of the three comparison feedstocks. By the change in annual revenue alone one can see that the big increase to MSP IPK revenue of $15 MM/yr from higher polysaccharides for pulp chips is diminished by a reduction in LS revenue of about about $2 MM/yr for less LS. Likewise, the $46 MM/yr lower MKT IPK revenue for hog fuel feedstock (from lower polysaccharides due to much higher bark content) is moderated somewhat by a gain of about $6MM/yr in LS revenue.

Table FS2-2.4. Impact of lignin and extractives on lignosulfonates revenue

LS Amount and Revenue			
	FS-01	FS-10	FS-08
	DF Pulp Chip Accepts	DF FHR Accepts	Hog Fuel Accepts
Lignin percentage	27.9	30.4	34.4
Soluble lignin to SSL, % of feed	6.42	6.98	7.91
Extractives %	6.2	7.0	9.3
Soluble extractives to SSL, % of feed	5.5	6.2	9.1
Lignin + Extractive to SSL, % of feed	11.88	13.18	17.00
Annual Weight going to LS from L+E, BDT	91,660	101,740	131,236
Change in weight from V 13.43 base case	-10,080	0	29,496
Total Annual LS to sell, BDT	186,144	196,224	225,720
Annual Revenue from LS, $MM	$37.23	$39.24	$45.14
Annual revenue change from base, $MM	**-$2**	**$0**	**$6**
Percent change against FS-10 case LS revenue	-5%	0%	15%

Lignin and extractives to activated carbon - results

As described earlier, portions of the changed lignin and extractives—those insoluble in SSL—are sent to AC production (along with unfermented sugars, yeast bodies, and other compounds), where all FRS mass gets a 18.8% yield to AC. Strictly speaking, the ~80% that does *not* go to AC ends up as volatile gas used for power generation, so there would be some energy cost change (increase or reduction in purchased hog fuel), however this is a second-order effect and will be ignored here. Table FS2.2.5 shows the calculations for impact of the three feedstocks composition on annual AC revenue.

Note that the actual annual L+E *quantity* changes going to AC production are very similar to the LS amount change for each feedstock alternative. Because the AC has an 18.8% yield on FRS feed, but the selling price is 7.5 times as high as for LS ($1,500/BDT for AC and $200/BDT for LS), the net economic impact of L+E changes for AC *revenue* is similar to that of LS—that is, lower L+E of pulp chips reduces AC revenue about $4MM/yr, and higher L+E of hog fuel increases AC revenue about $5MM/yr.

Table FS2-2.5. Impact of lignin and extractives on activated carbon revenue

AC Amount and Revenue			
	FS-01	FS-10	FS-08
	DF Pulp Chip Accepts	DF FHR Accepts	Hog Fuel Accepts
Lignin percentage	27.9	30.4	34.4
Insoluble lignin to AC, % of feed	21.48	23.38	26.48
Extractives %	6.2	7.0	9.3
Insoluble extractives to AC, % of feed	0.7	0.8	0.2
Lignin + Extractive to AC, % of feed	22.23	24.23	26.72
Annual Weight going to AC from L+E, BDT	171,535	186,963	206,179
Change in weight from V 13.43 base case	-15,428	0	19,216
Total Annual AC to sell, BDT	63,291	66,192	69,805
Annual Revenue from AC $MM	$94.94	$99.29	$104.71
Annual revenue change from base, $MM	**-$4**	**$0**	**$5**
Percent change against FS-10 case revenue	-4%	0%	5%

[2] The NARA ASPEN model does not track water soluble and ethanol soluble extractives separately—just the total, so we use that basis here.

Net effect of IPK, AC and LS on annual revenue

When we net out the changes in all three product revenue streams (using MSP IPK case) and compare to the cost differences for the feedstock alternatives considered, we get results as shown in Table FS2-2.6.

Table FS2-2.6. Net impact on feedstock cost and revenue for 3 feedstock alternatives (for the MSP IPK scenario).

Net Revenue Impact of IPK, AC, and LS			
	FS-01	FS-10	FS-08
	DF Pulp Chip Accepts	DF FHR Accepts	Hog Fuel Accepts
Annual change from MSP IPK, $MM	$15	$0	-$46
Annual change from AC $MM	-$2	$0	$6
Annual change from LS $MM	-$4	$0	$5
Net Revenue Impact of MSP IPK, AC, and LS	$9	$0	-$34
Assumed Feedstock Price to conversion	$126.20	$64.28	$45.00
Annual Feedstock Cost Change, $MM/yr	$48	$0	-$15
Net Annual Change, Revenue-FS Cost, $MM/yr	-$39	$0	-$19
V 13.43 MSP IRR with that FS price	**6.8%**	**10.0%**	**8.7%**

Higher polysaccharides content of pulp chips gives $15 MM/yr added IPK revenue while only decreasing AC_LS revenue about $6 MM/yr, for a $9 MM/yr net revenue gain. But the higher cost of the pulp chips increases feedstock cost by $48 MM/yr, netting out to a $39 MM/yr poorer economic case that the base case FHR. This reduces the MSP IRR from 10% in the base case to 6.8% for pulp chips.

Hog fuel has about $46 MM/yr less in MSP IPK revenue, but gains about $12 MM/yr in AC+LS revenue, netting out to a $34 MM/yr revenue reduction. But feedstock costs are $15 MM/yr less, so the net case is actually somewhat better than pulp chips, netting out to “only” a $19 MM/yr poorer economic case than the FHR base case, resulting in an MSP IRR of 8.7%.

Ash content Impacts – assumptions

The last remaining feedstock component of any significant quantity is ash content, which in the base case FHR and pulp chips is almost trivial, but this is not so for hog fuel (with ~6% ash). Since this is inorganic material it almost certainly does not go into solution in SSL, thus will not make it to the SSL stillage nor the LS product. The inorganic material certainly will not ferment to IBA, nor go to the atmosphere, thus does not end up in IPK. It will not volatilize during AC production thus not go to volatile gas boiler, thus it must end up incorporated into the AC.

Since the materials in the ash are likely calcium carbonate and silicon dioxide (from soil), they will not volatilize like hydrocarbons in the AC process, thus do not have the assumed 18.8% yield. Additionally, the assumption that no change in AC properties would occur is *not* a good assumption. If 6% of the feedstock ended up going to AC in the FRS, and none of it was volatilized, the proportion of mass in the AC (at 20% yield on FRS) would be very large, and very likely diminish the quality of the AC, thus changing the market price.

Ash content – results

Since both the yield and the quality for ash to AC are probably far outside our simplification assumptions, and since hog fuel has so much ash and is economically inferior even without considering ash content, no further effort will be expended here to quantify how much worse the ash content makes hog fuel. Ash content probably needs to be kept in the realm found to be suitable for power production uses—something in the 1.5% range. It should be noted that high ash content likely has other process impacts that cannot be readily assessed at small scale, as problems likely build up over time in a real process. Realistically assessing economic impact of varying ash content is simply outside the scope of this work.

Discussion

Our detailed basis for the overall IBR mass and energy balance is the ASPEN model, where every flow is numbered, labeled and quantified. Figure FS2-2.3 shows the detailed overview with all ASPEN flows numbered, but without the quantities listed. For every process department shown the ASPEN model has a complete mass flow tracking of every listed flow. One can see that it is overly complex for understanding where, even in the base case FS-10, materials go to end up as product amounts, much less understanding how changes in feedstock composition will affect that, and the eventual impact on IBR economics.

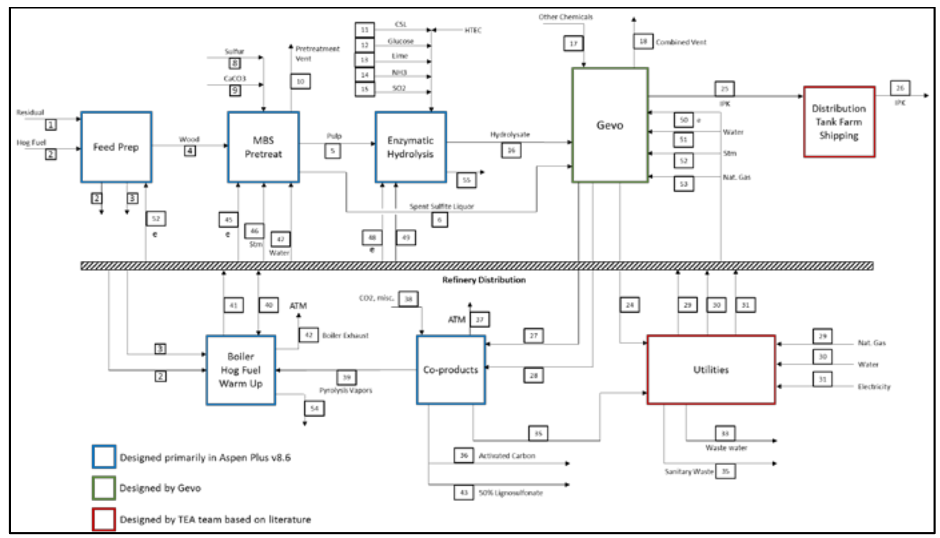


Figure FS2-2.3. Detailed IBR overview from ASPEN with main quantified flows.

To help better understand *why* we obtain these results for different feedstocks it is useful to understand at a high level where incoming feedstock mass components go w.r.t. end products sold, gases to atmosphere, solids to waste landfill. Note that the liquid output product (IPK), normally expressed in gallons, is now converted to a mass basis (per IPK specific density of 0.75, or 6.248 lbs/gal). Water flows that do not impact final product amounts are also ignored (some water is *added* to the sugar monomers in the hydrolysis reaction, some water is *removed* from IBA in dehydration step of ATJ). Figure FS2-2.4 shows our draft of a high-level "simplified" overview of the mass balance for the base case of FS-10, with main inputs and outputs to the closed box of the IBR (based on details in the ASPEN quantified flows).

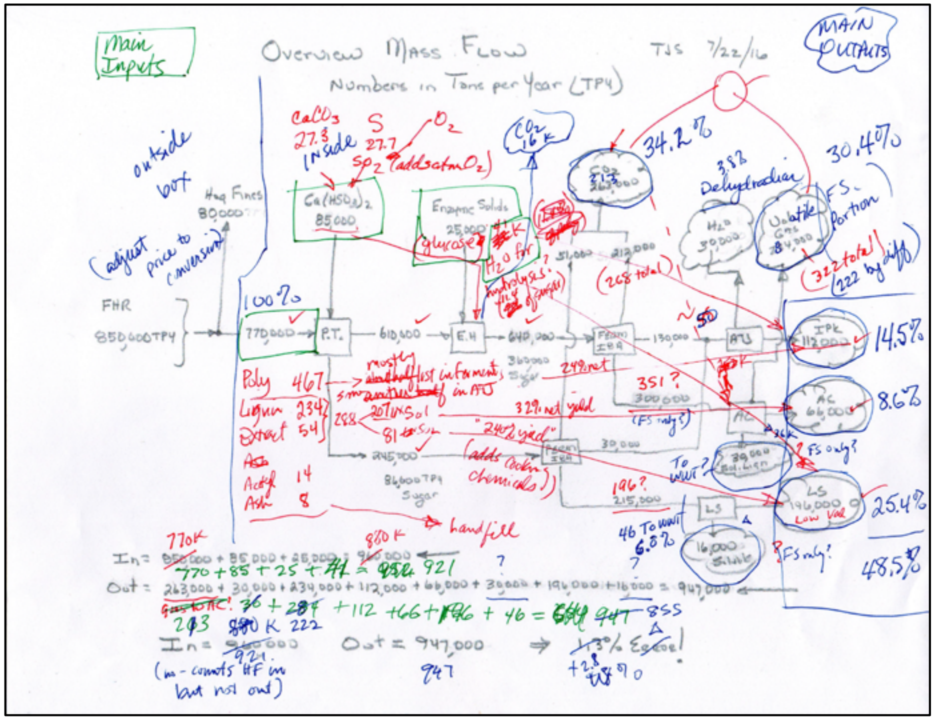


Figure FS2-2.4. Draft of high-level simplified mass balance overview.

First note that it is difficult to simply portray "how does the input feedstock flow to output products, and where does the remainder of the feedstock go?" because: a) there are other non-trivial input flows (e.g., cooking chemicals); b) there are both reaction incorporations of water into products (enzymatic hydrolysis of polysaccharides to monosaccharaides) and removal from products (dehydration of IPK in ATJ process; c) a large portion of one of the final products does not arise from feedstock (the cooking chemicals that end up in LS); and d) a non-trivial proportion of a major outflow (CO_2 to the atmosphere) includes incorporation of oxygen from the combustion air. In order to simplify the portrayal and maintain focus on how feedstock changes impact mass flows and resulting dollars, we make the following simplifications to the ASPEN detailed mass flows.

1. Glucose added to enzymatic production (~25 ktpy) is largely consumed during respiration to produce enzymes, and emitted back to atmosphere as CO_2 (~16 ktpy). For the resolution of this analysis those are considered a wash and both flows removed from the simplification.

2. The water added to monomers in hydrolysis (~41 ktpy) is largely offset by later dehydration of IPK in the ATJ block (~30 ktpy)—again nearly a wash given our level of resolution in the simplified balance.

3. Since it is very complex to calculate how much of oxygen in the CO_2 emitted from vents to the atmosphere came from combustion air, and how much came from feedstocks, we solve for a net balance in weight of input feed stocks, after accounting for all other output flows—by difference for the emission at the major carbon loss center—the volatile gas boiler vent in AC production. Empirically this results in about 222k BDT/yr CO_2 from feedstock source, compared to the total CO_2 shown in ASPEN of 263k BDT/yr—this seems reasonable.

These simplifications leave only one significant input flow aside from feedstock—the cooking bisulfite chemicals (at 52 ktpy), and these largely flow directly through to incorporation into the LS product weight (comprising about 25% of the final 196 ktpy weight of LS that is sold).

Of the 770k BDT/yr feedstock input mass to conversion, about 14.5% ends up as IPK, 18.7% ends up in LS, and 8.6% ends up in AC, accounting for 41.8% of the input feedstock mass.

The majority of the remaining feedstock exits the system as CO_2—about half of that from fermentation and half from the AC pyrolysis vapors boiler vent. (In this analysis we exclude oxygen that was incorporated from atmospheric combustion air, accounting only for carbon and oxygen coming in with feedstocks.) This CO_2 output flow accounts for about 49% of the input feedstock mass.

There is a relatively small flow of insoluble material from inorganic ash and various filtrates that goes either directly to—or through wastewater treatment as remaining sludge—to landfill. This flow accounts for about 4% of the incoming FS mass.

These simplified key flows are shown in Figure FS2-2.5.

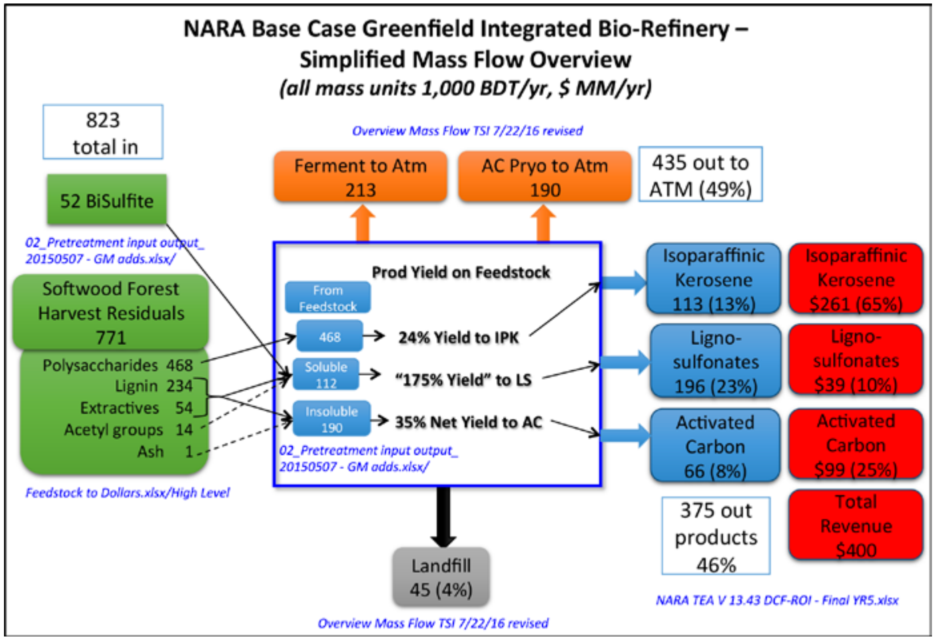


Figure FS2-2.5. Simplified Mass Balance overview.

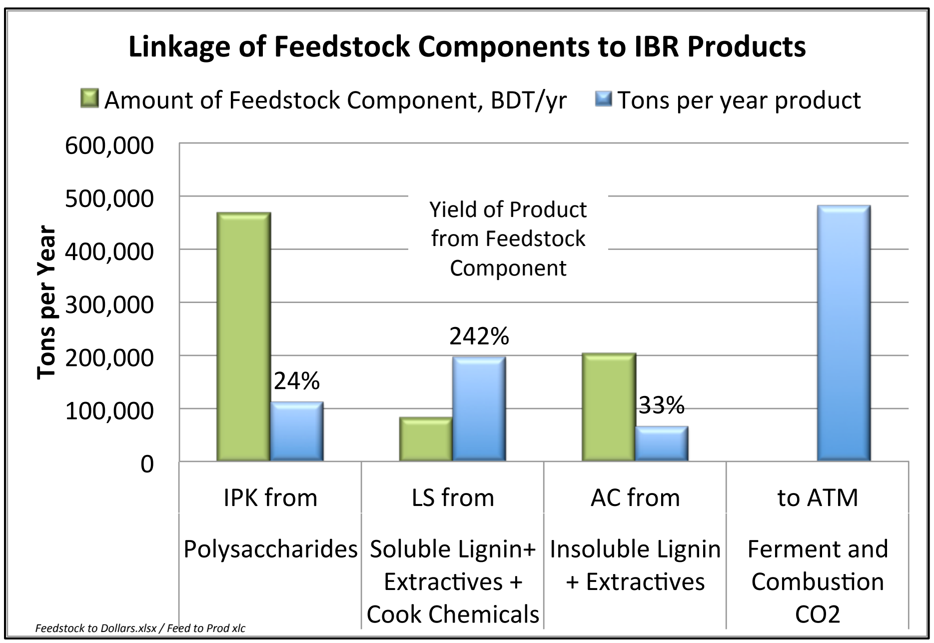


Figure FS2-2.6. Approximate linkage ("Yield") of feedstock components to products.

Understanding feedstock component eventual contributions to revenue

To better understand how the feedstock components link to final products and revenue, Figure FS2-2.6 portrays the proportional mass flows from input feedstock components to product mass.

Figure FS2-2.7 shows then the relatively linkage between product mass and resulting revenue, where the higher unit value of IPK drives much of the IBR revenue, despite relatively little product mass.

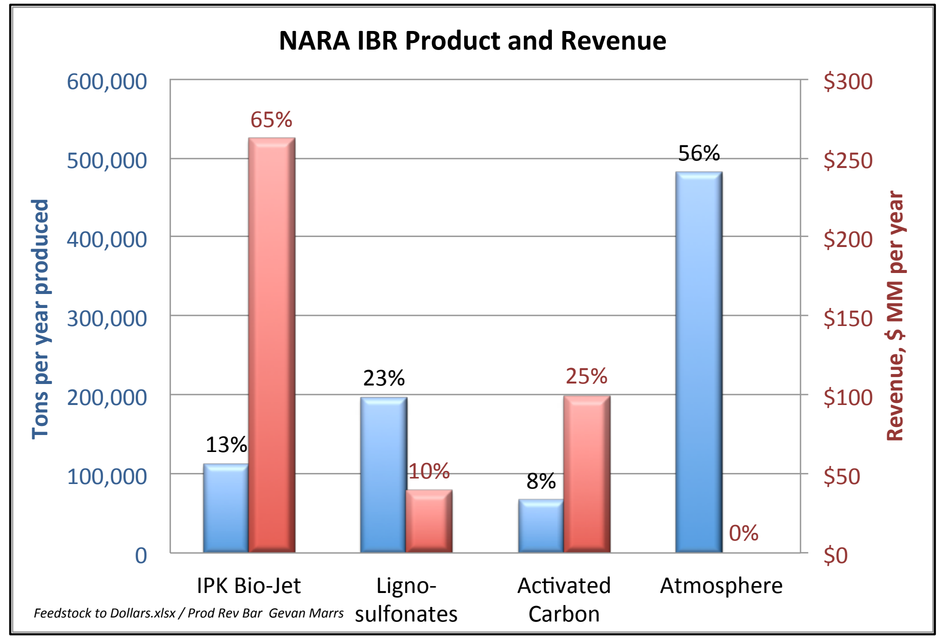


Figure FS2-2.7. NARA IBR output product relative mass and revenue generation.

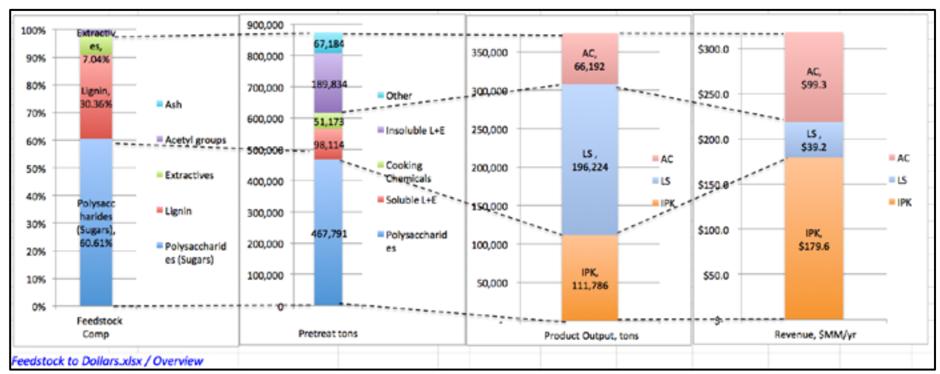


Figure FS2-2.8. Flows of main feedstock components through pretreatment, to products, and then to revenue generation on an annual basis.

To show the overall view of how feedstock major components pass through pre-treatment and on to products and then revenue, Figure FS2-2.8 shows all four stages in a single diagram.

The polysaccharides, the most prevalent feedstock component, produce the IPK at a relatively low yield, but it is high unit value (MSP case), so contributes the lion's share of IBR revenue. The lignin plus extractives—the next largest feedstock component—goes largely as insoluble fraction to AC production at a relatively low yield, but again with a relatively high unit value, leading to an important fraction of the IBR revenue. Lastly, the soluble portion of the lignin and extractives, even combined with other soluble materials (including the MBS cooking chemicals) is the largest product quantity produced, yet it has a low unit value, thus only contributes a relatively small portion of the IBR revenue.

Other FHR feedstock choices

This analysis so far has focused on so-called "extreme" options for sourcing – "clean" pulp chips and "dirty" hog fuel. Knowing now that FHR (at least FS-10) has the best economic balance of likely cost to conversion mouth and resulting product mix value, it may be instructive to consider the range of options for just the FHR category of materials in order to better understand the range of likely results if the delivered price were constant (e.g., FHR at $62.60/BDT).

The majority of NARA feedstocks tested were screened into Accepts and Fines fractions, and these tested separately. When all tested NARA feedstocks (including the fines fractions) are first grouped by Accepts and Fines, then sorted in order of declining polysaccharides content, relationships between other components can be discerned (Figure FS2-2.9).

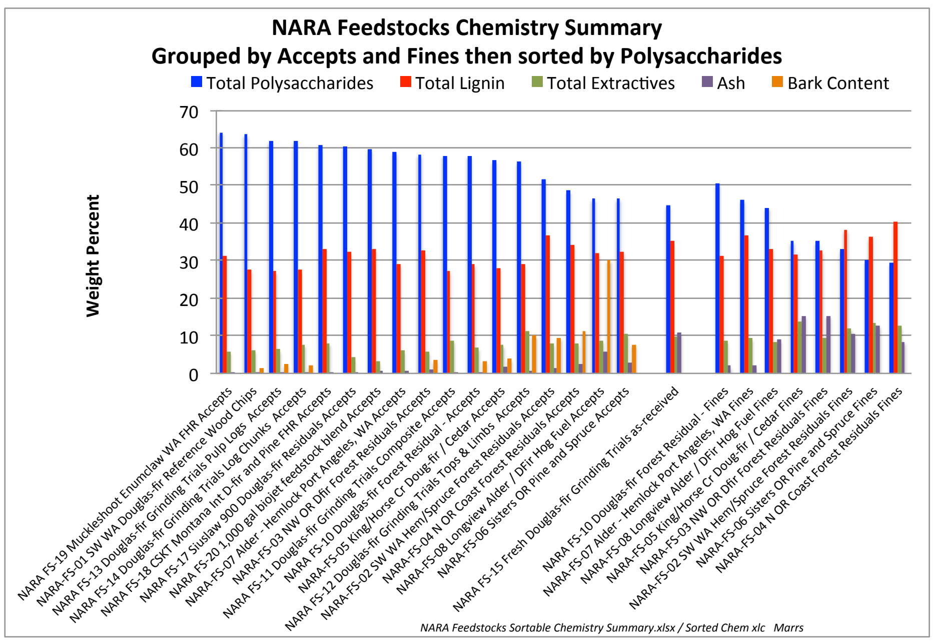


Figure FS2-2.9. Grouped and sorted NARA feedstocks key chemical properties.

It can be seen that in general, declining polysaccharides content are countered by increasing lignin and / or extractives content. The groups of Accepts and Fines generally shows the merit in screening out fines for routing to energy production—that is, fines have much lower polysaccharides and higher lignin and extractives. The underlying causes of the differences in composition have to do mostly with two factors: bark content and species.

Bark content is influenced mostly by the choice of materials to place in the grinder—selecting tops and branches results in relatively more bark (e.g. FS-12 at about 10%) compared to pulp logs or chunks, or selected larger pieces (FS-13, 14 and 19 at 1.5 to 2.5% bark). Fresh material can retain much more bark as well (NM).

Species impacts mostly arise from hardwoods vs. softwoods. As noted in an exhaustive survey of the literature (Fengel, 1975), as reported at http://www.carbolea.ul.ie/wood.php. "*A detailed compilation of the polysaccharide and ligneous composition of wood was carried out by (Fengel and Grosser, 1975). By tabulating the data from more than 350 references in 153 temperate species it was found that, on average, stem wood in softwoods contains 40-45% cellulose, 25-35% lignin, and 25-30% hemicelluloses. Stem wood in temperate-zone hardwoods contains 40-50% cellulose, 20-25% lignin, and 25-35% hemicelluloses.*" That is, hardwoods tend to have about 10% less lignin that softwoods, and the difference is in higher polysaccharides in hardwoods. The Handbook of Wood Chemistry, (Petterson, 1984), shows in their Table 3.1 the data shown in Table FS2-2.7.

Table FS2-2.7. Summary properties for hardwoods and softwoods. Reprinted from The chemical composition of wood. In: The Chemistry of Solid Wood, by Pettersen, R.C., 1984. Rowell, R. M., Editor, Advances in Chemistry Series 20, American Chemical Society.

TABLE 3.1
Summary of Carbohydrate, Lignin, and Ash Compositions for U.S. Hardwoods and Softwoods

Species	Holocellulose	Alpha Cellulose	Pentosans	Klason Lignin	Ash
Hardwoods	71.7 ± 5.7	45.4 ± 3.5	19.3 ± 2.2	23.0 ± 3.0	0.5 ± 0.3
Softwoods	64.5 ± 4.6	43.7 ± 2.6	−9.8 ± 2.2	28.8 ± 2.6	0.3 ± 0.1

Source: Pettersen, 1984.

While the differences in higher polysaccharides and lower lignin for hardwoods is less than the extreme differences of bark composition compared to wood, the differences are large enough to impact total feedstock mixture composition and thus overall economics.

Conclusions

For the main economic impact of the major feedstock component shifts (polysaccharides changes offset mostly by the sum of lignin and extractives changes in the opposite direction), increases in polysaccharides lead to gains in IPK revenue (when sold at MSP 10%) that are roughly 2 or 3 times as impactful on net revenue as the off-setting changes in LS + AC revenue. That is to say, *if* all feedstocks were the same price through the gate, higher polysaccharides would definitely be preferred.

However, because the pulp chip feedstock is valued precisely because of the cellulose fiber content (for pulp and paper), the market demand drives it to a higher price than FHR. In the other direction, the very high bark and ash content of hog fuel limit's it's market demand to energy production, setting a relatively low value. These differing feedstock prices then more than counteract the net revenue changes resulting in both pulp chips and hog fuel being economically less preferable than FHR.

Within the categories of just FHR options, *if* we assume that any of them could be delivered at the same price (say, $62.60/BDT to the gate) with similar fines rejects (thus net cost to conversion), and we consider only the chemical compositions differences on product amounts and revenue, we find *as much or more variation in key components as for the clean pulp chips to hog fuel range*. Therefore, the higher polysaccharides content FHR material has higher IRR under both projected and MSP IPK pricing cases.

In other words, both producers and buyers (users) of FHR, *at equal cost to the gate*, should prefer those materials with higher polysaccharides and lower lignin-extractives, This can most readily be obtained by having low bark content and including hardwoods where possible. Low bark content is achieved by choosing material that has been exposed for some time to the elements as well as choosing relatively larger piece sizes (logs rather than branches). However, selecting only portions of a slash pile, would slow production and reduce quantities harvestable from each site, thus will not allow the same delivered cost. It seems very likely piece size selection in a pile is counter-productive, even to obtain a somewhat lower bark content, although it would take additional analysis to determine this precisely.

Summary

In a simplified view of the IBR, 467 k tons per year of the largest feedstock component—the 60% of feedstock consisting of **polysaccharides**—go to conversion. From these polysaccharides 113k tons of IPK are produced, giving an effective 24% yield on polysaccharides. The bulk of the remaining polysaccharides go to CO_2 from fermentation, although some makes it through to AC production as recycled CO_2 or and some go to FRS (yeast bodies, unfermented sugars, etc). The unit value of IPK in the MSP case is relatively high at ~$1,600 / ton, accounting for 65% of the IBR revenue.

The next largest FHR components—**lignin and extractives** (L+E) (accounting for about 36% of the feedstock)—deliver about 288 k tons per year to conversion, and these are split into the portion soluble in the MBS liquor (SSL)—about 112 k tons per year with the remaining 190 k tons insoluble. The soluble L+E goes without yield loss to LS, which also collects a nearly equal amount of cooking chemicals as well, resulting in a "175%" yield to LS (based on L+E) of 196 k tons per year. The unit value of LS is relatively low at $200 / ton, thus only 10% of the IBR revenue comes from LS despite being the largest tonnage product sold.

The insoluble portion of the L+E—about 190 k tons per year is combined with other materials from FRS to result in about 330 k tons per year input to AC, but with a ~20% yield on pyrolysis of the FRS, the majority is sent to energy production as pyrolysis vapors where after combustion it is sent as CO_2 into the atmosphere. This gives a net "yield" expressed on just the L+E portion of about 33% yield, or 66 k tons per year AC. The unit value of AC is relatively high at $1,500 / ton, but with only 66 k tons produced it accounts for 25% of the IBR revenue.

These four elements—the amount of polysaccharides, lignin and extractives in the feedstock, the yields to final products, the unit revenue for each product, and the main identifiable factor influencing the FHR composition—leave us with **bark content** as the principle factor over which suppliers and purchasers can attempt to alter and set specifications for in feedstock for a NARA-type IBR. Higher bark content results in lower polysaccharides, which give less IPK which reduces IBR revenue more than the offsetting gains in LS and AC production from lignin and extractives (which go up when polysaccharides increase). For the same delivered price, one would prefer lower bark content, all else being equal.

NARA OUTPUTS

1. Poster for Sep-2012 NARA Annual meeting, Missoula MT: *NARA Feedstock Sourcing poster- Quantity and Cost*, Gevan Marrs.

2. Powerpoint presentation for 2013 NARA Annual Meeting working groups, Corvallis, OR: *Feedstock Logistics – Sourcing Initial Availability Assumptions*, 6-Sep-13, Gevan Marrs.

3. Powerpoint presentation for 2013 NARA Annual Meeting working groups, Corvallis, OR: *Feedstock Key Learnings- Marrs*, 6-Sep-13, Gevan Marrs.

4. Powerpoint presentation for 2013 NARA Annual Meeting working groups, Corvallis, OR: *NARA TEA - Facility Scale - Marrs Feb-13*, 6-Sep-13, Gevan Marrs.

5. Powerpoint presentation: "*Economic Impacts of Forest Residue Feedstocks Preparation for Biofuels*" 29-Apr-14, NWBB meeting (NARA Annual Meeting) Seattle, Gevan Marrs - Weyerhaeuser Company, John Sessions – OSU, Rene Zamora – OSU

6. Excel spreadsheet database of all measured properties of NARA feedstocks: *NARA Feedstocks Tracking.*

7. Peer-reviewed publication: Rene Zamora-Cristales , John Sessions , David Smith, Gevan Marrs (2015). Effect of grinder configuration on forest biomass bulk density, particle size distribution and fuel consumption. *Biomass and Bioenergy*, 81, 44–54.

8. NARA report: 2014 Marrs, G R, *Testing WY Feedstock Analytical Results against NIST Reference Samples using NREL analysis procedures***,** NARA report.

9. Marrs, G., R. Zamora and J. Sessions. 2014. *Optimizing the Feedstock Value Chain for Bio-Jet Fuel from Pacific Northwest Softwood Harvest Residues,* "Biomass-Based Materials and Technologies for Energy" sponsored by Advances in Materials Science and Engineering.

NARA OUTCOMES

Change in knowledge

The feedstock characterization data, located on an Excel spreadsheet and stored at https://research.libraries.wsu.edu/xmlui/handle/2376/6460, can be utilized by many others who may want to consider at an initial level the suitability of these feedstocks for other bio-conversion processes.

The demonstration of final revenue impacts due to different feedstock compositions can help both buyers and producers of FHR for biofuels and co-products understand better the inherent value of different choices for quality. In particular, higher polysaccharides content—achieved most readily via reduced bark content—gives a powerful improvement in IPK production and thus IBR revenue, as long as it doesn't increase the delivered cost of the feedstock inordinately.

FUTURE DEVELOPMENT

The conclusions reached in this report lead us to two plausible feedstock quality improvement actions that could be further evaluated for merit. The first is the already-assumed screening of fines from the FHR. Since we measured the composition of the fines as well, and know the percentages rejected, we could mathematically reconstitute the incoming FHR composition (which would be higher in bark content, thus lower in polysaccharides and higher in lignin and extractives) and thus reduce IPK amount and revenue more than increase the AC and LS revenue. The question is whether the cost to of screening the feedstock is more or less than the gain in revenue to do so. Although is seems likely, the actual calculations were not within the scope of original NARA deliverables so have not yet been made.

A second option (for which we have empirical data from the "Grinding Trials" to apply) is the option to sort the kinds of material loaded into the grinder in the woods harvesting site. Choosing materials that had lower bark content (small logs and chunks) and avoiding branches would (based on measured composition of these material types—see FS-12, 13, and 14 in Table FS2-1.2) reduce bark, thus increase polysaccharides and lower lignin and extractives, thus provide more revenue to the IBR. To determine whether this is an economic gain would require estimation of the added cost due to lower productivity of sorting and reduction of harvestable amounts on each site. (A non-trivial portion of allocated harvesting costs is the fixed cost of moving equipment between harvesting sites—a cost which must be spread over all harvested material, thus raising delivered costs if each site produces less material.) This evaluation is beyond the scope of the work reported here.

LIST OF REFERENCES

Fengel, D. & Grosser, D. (1975). Chemische zusammensetzung von Nadel- und Laubholzern. *Holz als Roh- und Werkstoff*, 33, 32-34. doi:10.1007/BF02612913

Marrs, G., Mulderig, B., Davio, D. & Burt, M. (2015). *Feedstock Sourcing: years 1 -3*. In: NARA Final Reports. Retrieved from https://research.libraries.wsu.edu/xmlui/handle/2376/5310

Marrs, G., Spink, T. & Gao, A. (2016). Process design and economics for biochemical conversion of softwood lignocellulosic biomass to isoparaffinic kerosene and lignin co-products. In: NARA Final Reports. Retrieved from https://research.libraries.wsu.edu/xmlui/handle/2376/5310

Pettersen, R.C. (1984). The chemical composition of wood. In: The Chemistry of Solid Wood, Rowell, R. M., Editor, Advances in Chemistry Series 20, American Chemical Society.

Robinson, J., Keating, J.D., Boussaid, A., Mansfield, S.D. & Saddler, J.N. (2002). The influence of bark on the fermentation of Douglas-fir whitewood pre-hydroly sates. *Appl Microbiol Biotechnol,* 59, 443–448. doi:10.1007/s00253-002-1055-z

Wooley, R., Zhu, J.Y., Gleisner, R., Hawkins, A., Starkey, P., Gao, J., Spink, T.,… Sessions, J. (2016). Production of 1,000 Gallons of Biojet in the NARA Consortium. In NARA Final Reports. Retrieved from https://research.libraries.wsu.edu/xmlui/handle/2376/5310

Zhang, C., Zhu, J.Y., Gleisner, R. & Sessions, J. (2012). Fractionation of forest residues of Douglas-fir for fermentable sugar production by SPORL pretreatment. *BioEnergy Research*, 5, 978-988. doi: 10.1007/s12155-012-9213-3

Appendix 1: Photographs of NARA feedstock FS-17 through FS-20

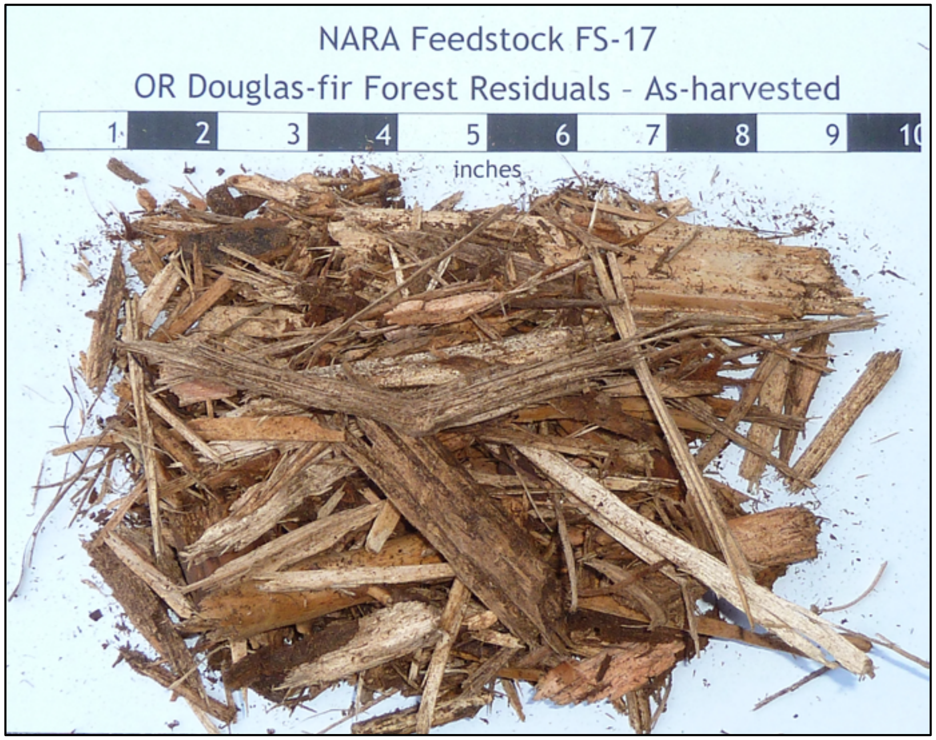


Figure FS2-A1.1. Nara feedstock FS-17

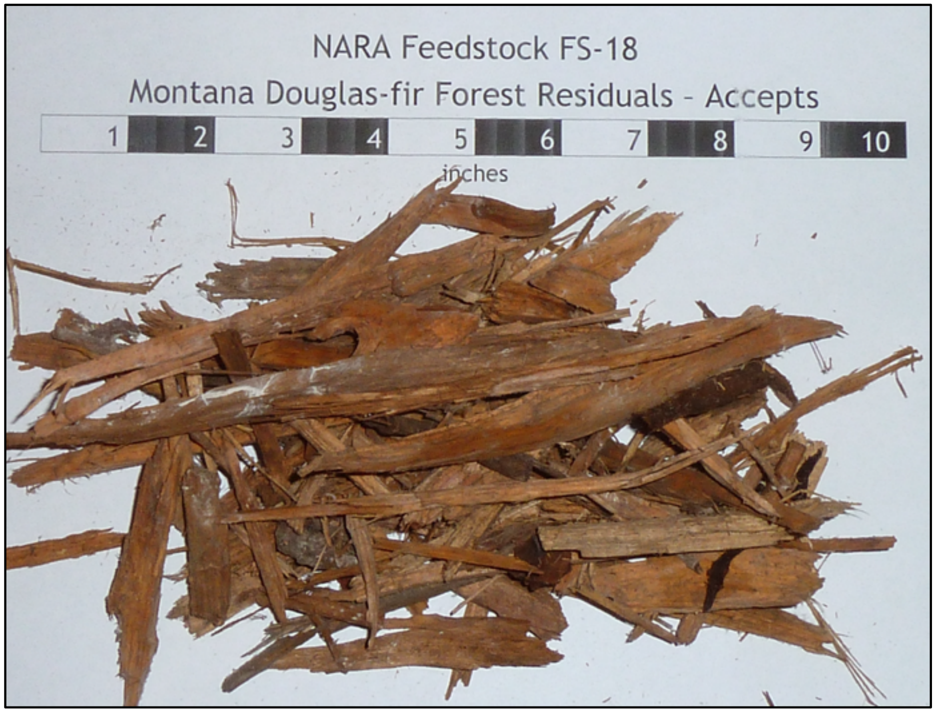


Figure FS2-A1.2. NARA feedstock FS-18.

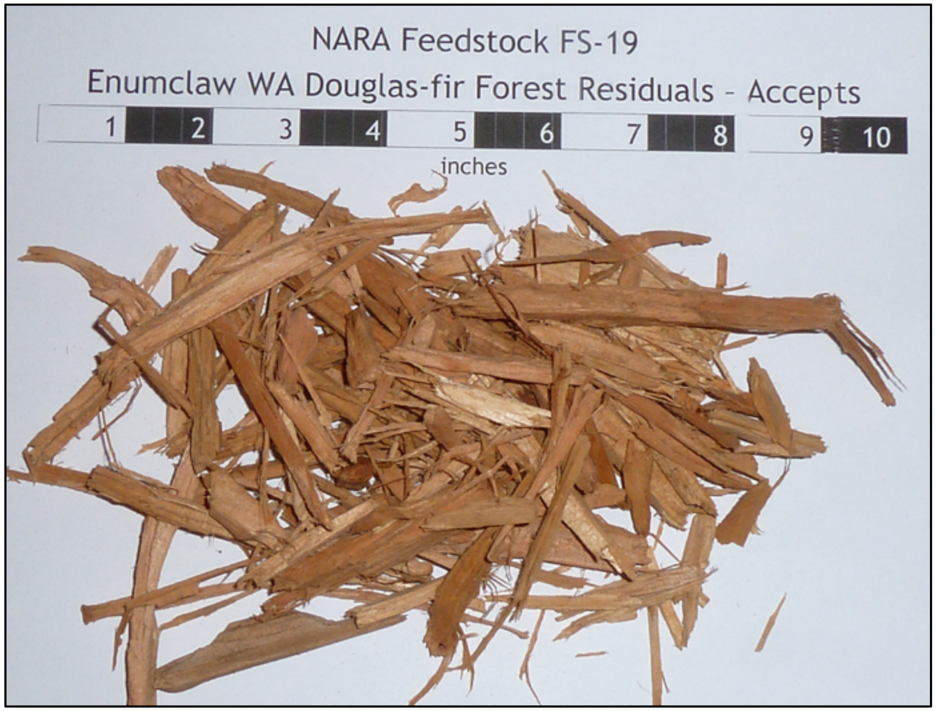


Figure FS2-A1.3. NARA feedstock FS-19

Figure FS2-A1.4. NARA feedstock FS-20

Appendix 2: NARA 1,000 gallon biojet production – Feedstock Preparation

5-Apr-15 Status – Gevan Marrs

Situation

We clearly needed to screen out oversize in FS-17 (Douglas-fir FHR from WY Siuslaw 900 Oregon site; Figure FS2.A2.1) and re-size them to reduce risk of plugging in the various feed systems for pilot scale conversion.

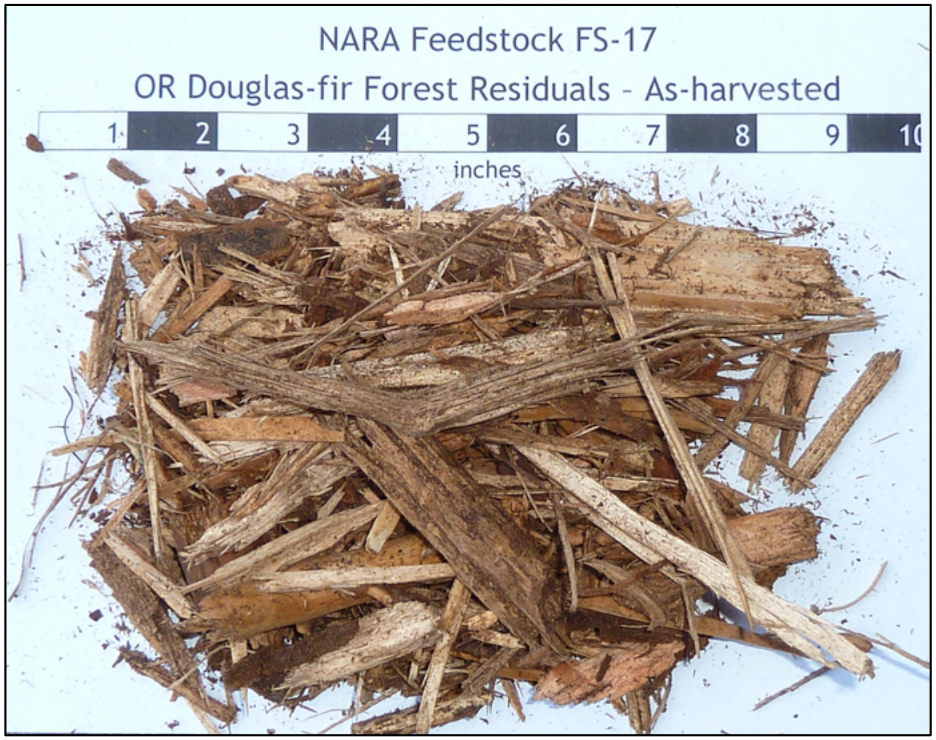


Figure FS2-A2.1. NARA FS-17 feedstock

The screening system available at Lane Forest Products Junction City yard is a vertical oscillation, wire mesh top deck with 1-inch square as the smallest oversize hole size available (Figure FS2-A2.2). It was estimated that FS-17 might reject between 30 and 50% of the material as oversize, which should leave the accept chips reasonably sized.

Figure FS2-A2.2. Screening system at Lane Forest Products

When actually screened, only about 15% of the FS-17 material was rejected as oversize (Figure FS2-A2.3). While it was definitely oversized, this left a lot of “sticks” in the accepts.

Figure FS2-A2.3. Oversized FS-17 screened with 1” woven-wire top deck. About 15% mass rejected.

Regrinding of the oversize in the horizontal grinder, with 1.5 inch grates, seemed to do a very good job of reducing the amount and size of “sticks”. There was some wind segregation in the pile, so the photos show the range of sizes produced (Figures FS2-A2.4; FS2-A2.5.) Incidentally, about 10% of the FS-17 feedstock was screened out as minus 1/8” fines (Figure FS2-A2.6; FS2-A2.7). ZeaChem staff expressed concern over the amount of larger pieces still left in the accepts.

Figure FS2-A2.4. FS-17 first pass screen accepts (-1”WW, +1/8” WW) FS-17, about 75% of feed.

Figure FS2-A2.5. Size range of FS-17 accepts (A and B).


Figure FS2-A2.6. Three FS-17 feedstock sizes: Oversize in foreground, Accepts in mid-shot, and Fines in the background.

Figure FS2-A2.7. FS-17 Fines.

Options

It is clear (to the authors) that the current screen, with the available top deck, will not remove the "sticks" that may be a problem. At this point some options are:

1. **Re-grind** all the current FS-17 screen accepts through the horizontal grinder with 1.5 inch grates. This will generate some fines, which we can either:
    a. **Leave in**, as they won't have the bark and grit removed in the first screening, or
    b. **Screen again** – although it is unclear how much will be removed as the fines seem to be pretty fibrous. Also, screening is quite slow compared to grinding, so will add another couple thousand dollars to preparation costs.
2. Investigate the options for **different screen top deck** for the current screen (e.g., round-hole punched plate with ¾ to 1 inch holes) and re-screen accepts.
3. Investigate alternatives for obtaining a **different screen** to be moved to Junction City yard and re-screen everything.

6-Apr-15 Update

- Held a phone conversation with ZeaChem staff, Wooley, Sessions, Marrs. Reviewed photos as well as a more general shot of the FS-17 Accepts (Figure FS2-A2.8):

Figure FS2-A2.8. FS-17 Accepts (-1"WW, +1/8"WW).

- ZeaChem staff still concerned about pieces that exceed 2.5 to 3 inches, of which there are likely more than a few in the current accepts.
- No particular concern about the finer fibers left in the re-ground overs, therefore, it was agreed that it would be prudent to:
    - Regrind all Accepts (overs have already been reground, but should be added back to accepts prior to re-grinding to keep masses correct and to help blending.
        - If possible, it would be prudent to swap out the first grate in the grinder to 1 inch (rather than the current 1.5 inch).
    - Rescreen all re-ground material, with a smaller top hole size (3/4 inch).
    - FS-20 Blend can be done AFTER the re-ground overs from each material are added to their respective accepts, but BEFORE the combined accepts and overs are re-ground. This then helps blend the FS-20 materials.

Specific Instructions for Lane Forest Products (as of noon 5-Apr-15)

1. Screen FS-18 Montana reground material. Done.
    a. Dispose of both fines and oversize.
2. Regrind the rest of the FS-17 Siuslaw Overs. Done
    a. These can be added back to FS-17 accepts. Done
3. ~~Regrind the FS-19 Washington screen overs, add them back to FS-19 Accepts.~~ Decided they were not needed to make the target blend, so disposed of the FS-19 overs.

Should then just have 3 piles on the ground at Lane Forest Products. Accepts plus Reground overs for a) Siuslaw, and one pile of screen accepts from re-ground Montana and b) Washington

4. Blend and remove about 5% of FS-17 weight from each of Montana and Washington piles, add these to Siuslaw 900 pile. Regrind everything through 1.5 grates. This becomes **FS-20A**. Done

Change of plans on 8-Apr-15 as a result of Wooley & Wolcott discussions at Zeachem.

5. ~~Regrind FS-20, perhaps using 1-inch first grates if available.~~
6. ~~Rescreen all FS-20 using a ¾ inch top deck and the same 1/8 inch bottom deck.~~
    ~~a. Weigh and dispose of fines and overs.~~

Revised target sizes and status as of 7AM 9-Apr-15

ZeaChem now feels far more comfortable with a ¼” average particle size. That is ***much*** smaller than our target of 5-Apr-15. It is not clear how we will ever reach that average size with grinding and screening equipment currently available at LFP Junction City, however, we can significantly reduce the amount of larger pieces in what we have now.

1. We now have a single pile of FS-20 blend, containing
    a. 90% Siuslaw 900 (FS-17) -1’,+1/8” accepts and reground (1.5’grate”) +1” overs (~248 green tons) and
    b. 5% FS-18 Montana reground, then screened accepts (~14 GT)
    c. 5% FS-19 Washington screened accepts (~14 GT) (Figure FS2-A2.9).
2. All of this FS-20 blend was reground with 1.5” grates, and this material is designated **FS-20A.**
3. We began to screen this on smaller screen holes, 1”, then ¾”, but stopped after a while as the accepts were still not considered small enough. This was labeled **FS-20-B**, but not sampled.

Figure FS2-A2.9. FS-17 Accepts and re-ground overs with 5% Washington and Montana Accepts added, ready to blend and re-size.

Our next option at LFP JC for significant additional reduction of this particle size was to re-re-grind all **FS-20A** material with the following four screen grates installed in horizontal drum grinder: blank, 1”, 1”, 1.5” (“b-1-1-1.5”). These are the smallest currently available. This grinding was first tested the afternoon of 8-Apr-15, with these results shown in Figure FS2-A2.10.

Figure FS2-A2.10. FS-20C test grind through horizontal grinder B-1-1-1.5 grates.

This size looks far more promising, but is still considerably larger than ¼”. Accordingly, **all** FS-20A was re-re-ground through B-1-1-1.5 grates, yielding FS-20C.

At this point we suspended LFP work to consult with NARA leadership on options.

We may still need to:

4. Re-screen the re-ground B-1-1-1.5 FS-20 on a relatively small hole size, even if we reject a considerable amount as “oversize”. If we don’t have enough accepts then, we can re-re-grind the overs and re-re-screen again.
    a. There was a small test of a 5/8” woven wire top deck in the screen today (9-Apr-15) to evaluate the resulting accepts. This yielded roughly 60% to accepts, which are sampled as FS020D and samples sent to Wolcott and Marrs for inspection 13-Apr-15.
    b. The +5/8” WW overs were designated FS-20-E.
    c. We might as well retain the 1/8” fines screens and take out some additional very fine material, unless this slows the screening process. If so we may want to forego the fines screening. The fines deck was blanked off during this last test.

The looming question is, who, and how, will we determine if the average particle size is sufficiently small to minimize conversion risk?

a. NARA staff make a judgment call

b. We send ~100 lbs to ZeaChem Boardman for them to "play" with and get their buy-in.

c. We send ~4 BDT to Andritz Ohio to try in feeder and blowline.

d. Other options?

Summary treatments by sample code

FS-20 : Blend of [95% FS-17 (Siuslaw) -1", +1/8 accepts and +1" overs reground with 1.5" grates] with 5% [FS-18 CSTK Montana re-ground through 1.5" grates, then screened on +1", -1/8", overs reground on 1.5" grates and added to accepts], and 5% [FS-19 Muckleshoot Washington screened accepts -1", +1/8"]

FS-20A: FS-20 re-ground with 1.5" grates.

FS-20B: Started re-screening on 1" top, accepts too big, switched to ¾" top, screened about 10 tons and stopped as target was moving.

FS-20C : Re-re-ground ALL FS-20A through smaller grinder grates: Blank-1"-1"-1.5" series. The vast bulk of the sample is now in this category (13-Apr-15).

FS-20D: Screened a small sample of FS-20C through 5/8" top deck. Got roughly 60% accepts, samples sent to Wolcott and Marrs 13-Apr-15.

FS-20-E: The oversize from the 5/8" screening of 20C. About 40% was oversize.

A conference call on 13-Apr with Marrs, Sessions, Wooley, Wolcott and Smith was held, wherein it was decided that the best option was the Crumbler technology at Forest Concepts, Auburn WA. It was agreed Gevan would visit and pursue. One-cubic-foot samples of each of FS-20-C, D, and E were overnighted to Gevan, who visited Forest Concepts on 16-Apr-15.

16-Apr-15 visit to Forest Concepts, Auburn WA

FS-20-F: They ran a ~5-lb sample of FS-20-C through the 3/16" Crumbler.

Ran 20-F over an orbital screen with ½" round hole punched plate top deck, 16 mesh ww screen bottom.

FS-20-G: Accepts -1/2", +16m.

FS-20-H: Overs +1/2" rh.

Hardly any -16 mesh fines – ignore.

Judged **FS-20-G** accepts to still contain too many large pieces. Re-ran just this accept material over the screen again with a 3/8" round hole punched plate, let the overs go in with the +1/2" overs. Net mass split was ___ to 20-I accepts and ___ to 20-J oversize.

FS-20-I: -3/8" round hole accepts from FS-20-F. Look much better as far as flow character.

FS-20-J: +3/8" rh pp oversize from 20-F.

FS-20-K: Recombined accepts FS-20-I and overs FS-20-J, through the Crumbler a second time and re-screened this on 3/8" rh pp (to add to the accepts). Converted perhaps half the oversize to accepts.

2nd test series – trying to get down to simplest process with decent yield.

Wanted to see if a single-pass with 3/8 screening would create acceptable material with a second pass. Recombined FS-20-D and FS-20-E samples (as it was decided we would NOT have to screen all FS-20-C at Junction City) so that we had more **FS-20-C** to test (4.975 kg). Ran this through the Crumbler once, screened on 3/8" rh pp.

FS-20-L: -3/8", +16 mesh ww accepts with one Crumbler pass. 3.285 kg (66% of feed)

FS-20-M: +3/8 rh pp from one Crumbler pass of FS-20-C. Weighed 1.355 kg. (*no sample taken)*

Did a second Crumbler pass on FS-20-M, the overs, and screened it on 3/8" rhpp.

FS-20-N: -3/8" accepts from second crumble of 20-M. Weighed 0.510 kg, or 10.3 % of feed. These would be added back to the first pass accepts for a total yield of about 76%.

FS-20-O: +3/8" overs after second Crumble of 20-M. Weighed 0.825 kg, or 16.5% of feed. In the proposed operation these would continuously be recycled back to the feed to Crumbler, so final net overs loss after quite a few passes would be quite low-certainly less than 10% of feed.

FS-20-P: Total 16 mesh fines rejects from entire second series runs. Weighed 0.335 kg, or 6.7% of feed. Not critical but easy to do and probably a good idea to get this material out of our feed.

4-May-15 Comparison of microchipped FS-20 to crumbled FS-20

FS-20-Q: Took samples from half each of 20-L and 20-N, from Forest Concepts Crumbling, and combined to emulate a "final" crumbling accepts.

FS-20-R: took Q and screened it on a 1/8" woven wire screen to remove more of the fines (it had been screened with 16 mesh at FC.)

FS-20-S: as-received FS-20-C chipped through the Peterson drum microchipper set for 1/8" at Lane Forest Products Junction City yard about 2-May-15.

FS-20-T: +3/8" Screened S on a 3/8" woven wire screen.

FS-20-U: Screened T on a 1/8" w/w screen – these are the fines passing the screen.

FS-20-V: Microchipped and screened accepts: -3/8" w/w, +1/8" w/w. About 60% of the mass of S.

Preparation of ~1 BDT for Andritz trial, Springfield OH

15 to 19-May-15

Decided our only option within time constraints was to do screening and crumbling at Forest Concepts, (FC) Auburn. LFP arranged for a self-dumping van to haul ~5 GT FS-20-C to Auburn. Per my specifications, FC had the 3/16" Crumbler set up in line with their 2'X4' gyratory screen equipped with 3/8" rh top deck, 1/8" w-w bottom deck. I visited and observed first test runs replicating FS-20-R above. There was still, to my eye, too many fines left in accepts with 1/8" w-w screen, changed to 3/16" w-w. Still too many fines in accepts. Increased to ¼" w/w. (Note that my hand-screening at 1/8" was "to refusal", whereas the FS screening was only a short exposure, hence use of larger openings to get similar level of fines out.) Started screening bulk lot at those conditions. Plus 3/8" rh material added back to feed and re-crumbled as trial progressed.

A problem was noted after a few hours – very low accept rates (9%) and high fines rejects (53%). At those rates we would not have sufficient accepts to ship to Andritz. Consulted by phone, then decided to shift to 3/16" w-w. Completed remaining screening, re-crumbled overs and re-screened, combining accepts. Blended all accepts – both from initial ¼" screening and 3/16" to create FS-20-Y. This material (1.08 BDT, 42% net yield to accepts) was bagged in supersacks and shipped to Andritz.

Bulk FS-20 preparation at Lane Forest Products, Junction City OR

29-May-15

Due to the tiny screen (a production bottleneck) at FC, it was not economically feasible to process remaining ~150 BDT in Auburn. Explored other screening options, concluded that nobody had a gyratory like we needed, so fell back to LFP and a CEC "Roadrunner" type vertical vibrating screen as only available option. Did some test screening with 3/8" w-w top deck, 3/16" w-w bottom. Seemed to give about 1/3 in each flow, but accepts looked good. Gave the go-ahead and screened all 150 BDT FS-20-C at LFP over the 29-May-15 to 1-Jun-15 period. Now need to wait for availability of Peterson microchipper to re-chip the +3/8" w-w overs.

June and July – John Sessions oversaw final preparation of the bulk of the feedstocks for the ZeaChem tests, done at Lane Forest Products. Although I don't have the full details at hand, essentially all material was screened to remove material larger than about 3/8", and less than 1/8" (as I recall) – a very narrow size cut. Then the "oversize was run through a Peterson horizontal drum microchipper set on 1/8 nominal chip cut length. This material then re-screened, and again overs were re-chipped. In the end there was approximately 60 BDT of material sized for ZeaChem specs. At 45 gal/BDT, we would only need about 21 BDT of feedstock, however there was expected to be significant pilot-scale inefficiencies and inevitable production problems encountered, so we wanted to have plenty of extra material.