VIABLE PRODUCTION OF DIESEL FROM NON-RECYCLABLE WASTE PLASTICS

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ABSTRACT

The art of refining liquid hydrocarbons (crude oil) into diesel, gasoline, and fuel oils was commercially scaled decades ago. Unfortunately, refineries are technologically limited to accepting only a very narrow range of liquid hydrocarbons with very specific properties and minimal contaminates. Unrecyclable, hydrocarbon-based waste is a significant environmental problem increasing every year. According to the Environmental Protection Agency's 2010 Facts and Figures report, over 92% of waste plastic is not recycled and with a growth rate of approximately 8% per year, there exists a critical need for a viable and environmentally sound, general purpose hydrocarbon-based recycling process. Hydrocarbon streams that fall outside of accepted refinery standards have traditionally been landfilled or melted into products of low value.

The barriers and challenges are so great that previous attempts to refine waste plastics into fuel resulted in unviable batch-based machines producing low-value, unstable mixed fuels. However, over the course of three years JBI, Inc. (“JBI”) has broken through these barriers and has designed and built a viable commercial-scale continuous refinery capable of processing a wide-range of hydrocarbon-based waste into ASTM specification fuels.

Research and testing of scale-up through 1-gallon, 3000 gallon, multi-kiln, and 40 ton/day processors took place in a plant in Niagara Falls, NY. Technical challenges encountered and lessons learned during process development will be explained in detail.

In 2009, our technology was “molecularly audited” by IsleChem, LLC (“IsleChem”) of Grand Island, NY and in 2012, the full-scale plant was viably validated by SAIC Energy, Environment & Infrastructure, LLC (“SAIC”). Numerous sources of waste plastic and users of the resulting fuel products conducted extensive audits of the technology, process, and plant. For the purpose of this paper, processing of waste plastics will be discussed in detail; however, this technology can be applied to other waste hydrocarbon-based materials such as contaminated monomers, waste oils, lubricants and other composite waste streams.

INTRODUCTION

Early research in this field has primarily involved a number of batch-based technologies, all with severe limitations. Properties, density, and preprocessing of waste plastics impose significant limitations on batch-based units.

Waste plastics have some of the most undesirable properties of any substance when considered for thermal processing. Plastics have low-surface area, poor heat transfer, exceptional tensile strength and are considered an insulator. During the melting process, plastics absorb heat and will stick to anything cooler, resulting in exigent “glue” that will seize or bind some of the largest high-torque feed technologies.
A common extruder utilizes a 300hp motor to liquefy 500kg/hr of plastics already preprocessed into pellets (Worner, 2011). Due to the cost of extrusion as well as vapor sealing issues, prior technologies opted for a batch design with feeding only when a reactor is cold. Densities of waste plastics are wide ranging from 2 lbs/ft³ for film, to 25 lbs/ft³ for high density plastics. Filling a fixed-volume batch reactor with waste plastics greatly limits production without expensive preprocessing and densification. Further, densifying waste plastic is both costly and energy expensive, as it is generally accomplished with extrusion-based pelletizers.

Preprocessing large plastic objects, which can include shredding, pelletizing, and contaminated ejection, can be expensive. Plastic does not behave like crude oil and therefore conventional refining technologies do not work. Most batch-based technologies are based on a process shown in Figure 1.

In addition to the significant limitations of batch-based processors on the input side, the output is also problematic. The resulting product is typically a low-flashpoint, unstable, unsaturated mix of random hydrocarbon chains, ranging from C5 to C80. Alkenes are undesirable in fuels and are highly reactive. This results in poor BTU value, high residue, and high THC’s when burned. Large refineries generally refuse these types of products due to their low value, impurities, acids, and possible damaging contaminates. The industrial users accepting these products are typically small refineries in need of source materials with the ability to feed these inferior products in very low ratios mixed with crude oil.

The residue resulting from batch-based processes can also be problematic, as coke which forms on the walls of the reactors or tubes must be scraped or drilled out at considerable time and expense. As prior attempts have not been permitted to use any low-boilers generated in the process, they cannot use what little gas they do produce as energy to assist in the heating and cracking process. The emissions from batch-based processes are generally not desirable and are usually required to have a thermal oxidizer to incinerate any volatiles, organics and low boil gas created in the process.

Three years ago, the work being undertaken at JBI sought to solve the aforementioned problems with an aggressive “must have” list for our process. The list included:

- Must be viable
- Must accept waste continuously
- Must accept waste with minimal power requirements (no extrusion)
- Must accept composite waste material with metals
- Must operate on the off-gas generated from cracking hydrocarbon chains
- Must have anti-coking technologies
- Must seal well

- Must be low-cost (our work was nominally financed)
- Must operate at atmospheric pressures (no vacuum or pressure vessels)
- Must generate in-specification ASTM D396 and ASTM D fuels for direct industry use

![Figure 1. Foundation of a typical batch-based process](image)

A detailed account of the challenges, solutions, and lessons learned throughout this work and research follows.

**PROCESS DEVELOPMENT**

In 2009, a small 1-gallon continuously charged reactor (Fig. 2) was assembled and operated for several months, gathering data relevant to scaling the process. The 1-gallon reactor was charged with 100g of plastic every 5 minutes. Over 44 runs, the reactor was charged with processing shredded waste plastics including: food waste packaging, agricultural film, and shredded gas tanks. High-density polyethylene (HDPE) regrind was used on some rungs to establish ideal conditions. The low-boilers (methane, ethane, butane, propane, and hydrogen) were analyzed with a gas chromatograph (GC) and quantified. The resulting fuels underwent typical petroleum testing including automatic distillation testing and flash and pour point evaluation. The fuel output consisted of a Diesel/Naphtha mix. The remarkable GC testing results of the output of the 1-gallon reactor is shown in Fig. 3. Note the absence of wax-like hydrocarbon chains in the C20-C60 range. Additionally, hydrocarbon production was predominately in the C13 diesel range.

The 1-gallon reactor was moved to IsleChem, formerly Occidental Petroleum’s research laboratory, to verify and assist in the scaling and permitting of the processor.

![Figure 2. 1 gallon reactor at IsleChem Dec. 2009](image)
During the time the 1-gallon reactor was being tested, the construction of a 55-gallon processor (Fig. 4) was accomplished. The processor was scaled up identically from the 1-gallon reactor with the added feature of being fueled by the low boiler gases created by the process. Remarkably, the fuel output product of the 55-gallon reactor was identical to the 1-gallon reactor. The process was repeatable, scalable, and could operate on its own low-boiler gases. The 1-gallon reactor was later expanded to include miniature towers to separate the diesel and gasoline fractions.

After four months of testing, on April 12, 2010, IsleChem issued a report (Appendix A) which concluded the following:

- Process was repeatable and scalable.
- 85-95% is converted to “near diesel” fuel.
- 8% is converted to usable off gas much like natural gas.
- 1% remains as residue.
- No evidence of air toxins in the emissions.
- The energy balance of the process is positive; that is, more energy value is produced than is consumed by the process. Early data suggests that it is by as much as a factor of two.

The results of the testing of the 1-gallon reactor proved environmentally friendly and viable, so much so that the New York State Department of Environmental Conservation (“NYSDEC”) issued a consent letter to construct a 3000-gallon reactor pilot plant (Fig. 5) to gather data and emission information for future air and waste permits.

In order to accomplish the aggressive task of building a pilot plant in less than 2 months, a special company culture was developed. Simply stated, a Silicon Valley-like startup structure was created in a plant with 20 talented people in Niagara Falls, NY consisting of chemists, welders, fabricators, chemical operators, material handlers, administration and security. Pride of ownership (company equity), incredibly long hours and perseverance drove this team to successfully complete a 3000-gallon pilot (Fig. 5) plant in less than 2 months.

The waste plastic flows through the process as shown in Figure 6, an image of the operator control screen. The waste plastic is loaded on a scaled hopper. The waste is fed through a series of slide gate valves to quarantine a specific volume of plastic. Oxygen is purged by feeding nitrogen into the space. The final slide-gate is opened to drop the waste plastic onto a screw conveyor. The screw conveyor is driven by a 2HP motor, so there is no power available to overcome any plastic if it begins to melt in transit. Initially plastic melted on the screw conveyor, binding it to the steel case. This was overcome by
applying a proprietary coating on the screw and rotating it at high speeds.

The 3000-gallon reactor is an indirectly fired kiln. The kiln is heated with a 4 MBtu Maxon burner combining low boilers from the process and city natural gas for startup and instantaneous short periods when low boilers are unavailable. The rotating kiln adds many desirable properties for the process including: automatic residue removal (similar to a cement truck) and tumbling plastic waste, which allows for effective heat transfer and homogenous mixing of the feedstock material. A rotating kiln also works well in a continuous process.

Some challenges encountered in this work were: sealing, coking, and heat transfer. Rotary kilns, by design, are difficult to completely seal, generally have poor heat transfer, and produce a coke residue on the inside walls of the kiln when exposed to high temperatures. As coke forms on the walls of reactors or kilns, it acts as an insulator thereby depriving heat inside. Unreasonable heat must be increased on the outside of the kiln to maintain internal temperatures. Eventually, heat must be removed and the coke scraped off the walls to allow for future operation. Thermal expansion also presented challenges when sealing and rotating.

The challenges were overcome quickly and our solutions proved effective. Special seals were developed to keep 400° C vapor (with hydrogen) from escaping on the input and output. The seal consists of a constant-pressure, multi-layer proprietary packing seal with a nitrogen purge. Effective heat transfer in the kiln is accomplished through a mechanical assembly that transfers heat to the plastic. This assembly also scrubs the coke off the walls ensuring that heat can be transferred to the insides of the kiln. A photograph (Fig. 7) depicts the coke-free inside of the kiln after processing 120,000 lbs of waste plastic. Generally, 2% of the waste plastic fed into the processor will result in petroleum coke. Due to the mechanical coke cleaning, the resulting residue is a fine carbon black that is easily removed with a screw conveyor.

The vapor leaving the 3000-gallon reactor contains a variety of fuels, some water vapor (if plastic was wet), hydrogen, methane, ethane, butane, and propane, and some nitrogen. One of the challenges imposed on this work was fine carbon black which from time to time became entrained in the vapor.

Figure 6. Pilot plant process

The vapor passes from the reactor through a “catalyst tower” (noted T1) which ensures the resulting fuels contain no halides. The column also facilitates the selection of the types of fuels to be produced. A cyclone was added between the reactor and T1 to capture fine carbon black entrained in the vapor.

The vapor then passes through a column designed to condense a specific fuel product; Naphtha, Fuel Oil #2 or Fuel Oil #6. This column also controls how much low-boiler gas is created for the process. The final tower is a water seal used to seal oxygen from entering the system.

<table>
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<th>Emission</th>
<th>Result</th>
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<tr>
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<tr>
<td>THC</td>
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Table 1. Stack Test Results, Processor #1—Conestoga Rovers 2010

After the fuel condenses, the resulting vapor is hydrogen, methane, ethane, butane, propane and possibly some water vapor. The vapor is compressed and redirected to the burners.

The “brain” of the process is a significant custom-programmed, data acquisition and control system (Fig. 8). Due
to the unique nature of the process, thermocouples, pressure sensors, a scale, an oxygen sensor, level sensors, and proximity sensors were installed throughout the system. Data is collected via a Honeywell HC900 PLC (“PLC”). The PLC is used to gather data and respond to automation actuation requests. Pumps, valves, and motors are all controlled by the PLC through contacts, 4-20mA loops, or MODBUS.

![Operator control screen for pilot plant with fuel separation](image)

The PLC is connected to an HP DL580 server. The operating system used was Ubuntu (Linux). A server-side program was written to capture and log data from the process every 10 seconds. In addition, the program controls all of the devices through the PLC. The server side program operates the chemical process through a user-generated C-style script program that can be modified at any time through the client program. Chemical operators interact with the process through custom software written to run on Windows or Ubuntu (Linux) operating systems. The process can be monitored and controlled through any one of the clients. This custom data acquisition and control system with on-the-fly script execution, allow for exceptionally fast evolution of the processor.

Initially, achieving steady state in the start-up of the process was fairly difficult, resulting in what would best be described as “running a marathon riddled with hurdles.” This quickly evolved into a process that had a very large, steady-state operating range of parameters.

Process safety is designed through various levels of hardware installed to ensure proper and safe operation. Early triggers for potentially unscheduled events are monitored by chemical operators, through the software managing the process. Risk is greatly reduced by operating the process at slightly above atmospheric pressure. Finally, there is a 12” burst disk at the output of the reactor to vent combustion should it occur. The burst disk successfully vents high pressures which, if they were to occur, could cause energetic disassembly of the processor. The processor was designed to store minimal fuel in-process. Less than 75 gallons of fuel is in the process at all times, which limits risk. Fuel production is limited to a few gallons per minute, thereby keeping the system manageable if pump failure were to occur. The safe design of this technology has resulted in zero time loss accidents during 3 years of process evolution.

An emissions stack test was conducted on the pilot plant less than 6 months after its construction. The stack test results shown in Table 1 verified that process emissions were very low and could operate within NYSDEC regulations referred to in a simple air permit. In December 2010, the NYSDEC issued a rare consent order for the plant to continue operating while air and solid waste permits were being acquired.

In its first year, the pilot plant produced in excess of 15,350 gallons of fuel.

**Separate Reactions and ASTM Spec Fuel Production**

In the successive generation of processors, it was determined that throughput and runtime could be improved by separating the reactions, which were previously all occurring in the main reactor. A standardized “fuel tower” was developed to handle each type of fuel produced in the system. These enhancements greatly improved runtime and fuel production. Additionally, they resulted in the production of ASTM specification fuels.

In early 2011, the system evolved to include a pre-melt reactor (rotary kiln), multiple fuel columns, and an internally designed low boiler compression system that could handle the various flows and volumes of low boilers the process generated. Low NOx burners were also installed to further reduce emissions. Two, 4.5MBtu burners were installed on each kiln to facilitate more heat. High volume, low head, high temperature pumps to move liquid fuel products up to 350°C were needed. Commercial centered-lined pumps at 350°C at 9 gpm averaged $40,000 each. Our team designed an application-specific pump for under $4,000 to significantly reduce costs.

The results of the enhanced process were remarkable. The system was capable of producing in-specification fuels with higher waste plastic feed rates.

![Processor with 24" feed and in-spec fuels](image)
In addition, a larger feeder was added to accommodate larger pieces of plastic. In the new processor shown in Figure 8 and Figure 9, plastic is fed via a 24-inch feeder (a significant upgrade to the 6-inch feeder of the pilot processor) to a pre-melt rotary kiln. Typical plastics fed into the large feeder include: off-spec Crayola Markers and Crayons, gas tanks, food packaging, wine bags, agricultural waste plastics and various scrap plastics from local industrial sources. The plastic is then melted into a liquid form.

The liquefying of plastic initially resulted in both benefits and challenges. By liquefying the plastic first, if contaminates like PVC were to get into the system, HCl could be separated and removed before fuel production in the reactor. Challenges arose from the undesirable properties of molten plastic. Molten plastic is highly endothermic and will freeze up in a pipe if pumped too far. In addition, molten plastic has widely varying viscosities depending on temperature and composition. Initially, the pre-melt kiln was located 30 feet away from the reactor kiln due to building limitations. Eventually, the pre-melt and reactor kilns were located as close as possible to each other, thereby limiting the chance of the molten plastic binding to the pipe and fouling.

The final 40T/day plant is pictured in Fig. 10. A stack test (Table 2) was successfully conducted in December 2011.

<table>
<thead>
<tr>
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<th>Result</th>
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Table 2. Stack Test Results, Processor #1 with premelt – Conestoga Rovers 2011

Figure 10. 40 T/day processor

Today: the 2% Challenge and Status of Operations

Over the past three years, as part of a structured commercialization plan, work focused on resolving problems in order of priorities. The initial primary focus was continually processing waste plastic and producing in-spec fuels consistently.

Once that had been accomplished, a new problem surfaced. The 2% residue would accumulate in the reactor until it was full. This necessitated taking the system out of steady state to remove the residue. The ability to run the process 24/7 for weeks without the pauses for residue removal is desirable and beneficial from a revenue and production standpoint. The existing process can convert anywhere from 120,000 lbs. to 160,000 lbs. of plastic between residue extractions. The existing process cannot make fuel or feed during residue removal.

In order to solve this challenge, a third kiln, half the length of the pre-melt and reactor is being introduced in the 3rd generation processor design. The addition of the third kiln will condition and remove coke and residue continuously. This will be done using a screw similar to the feeder but located at the end of the process. The estimated volume of residue is approximately 70 lbs/hr. This processor is currently being assembled.

Currently, plastic feedstock is provided by many large companies and municipalities across North America. Additionally, less dense plastic such as Agricultural film and shopping bags are being processed with denser plastics.

In March 2013, we had a significant breakthrough. We were able to develop a catalyst that allows our process to handle up to 20% PET and polycarbonate (PC) plastic contamination, without effecting processor operation or fuel quality. This is significant because the pyrolysis of PET and PC typically yield terephthalic acid and benzoic acid. Terephthalic acid generally sublimes and clogs piping in these types of processes. To date, this proved successful in the lab scale processor and we do not foresee any difficulty applying this solution to the 40 ton/day processors.

Additionally, we are working on feedstock pre-processing technologies that will enable us to dry and densify plastic during feeding. Due to the significant waste heat resulting from the process, we are exploring technologies that will dry and densify the feedstock by utilizing the waste heat from the process and excess electricity from cogeneration. Presently, the process is tolerant of plastic with moisture; However, excessive water and snow resulting from weather and other external factors can cause some problems during processing at this time.

The negative perceptions associated with “alternative fuel” were overcome through consistent fuel production quality,
extensive testing and government audits. The fuels created by the processor are Fuel Oil No. 6, Diesel, and Naphtha. Fuel Oil No. 6 and Naphtha do not require any additives and are shipped directly to a customer. The diesel fuel has very low sulphur so a lubricity additive is injected prior to shipping the fuel to a customer. The fuel has been tested by InterTek, Petrolabs, Southwest Research, and Alberta Research Council. Analysis of diesel fuel directly from processor 2 is shown in Figure 11.

The fuel from the plant is directly shipped to end-users including US Steel, Coco Paving, and several fuel distributors.

Additionally, waste liquid hydrocarbons were tested as a heat-transfer fluid in the process from October to December, 2012. A stack test was successfully conducted in December 2012. Results are shown in Table 3.

- Waste is charged continuously through a low-power feeder.
- Feedstock can include liquids or solids and does not need presorting.
- Approximately 86% of the waste is converted into a liquid fuel.
- The process is primarily powered from low-boiler gas produced.
- Diesel power generators converted for propane operate on low-boiler gas.
- The process emissions are less than that of a natural gas furnace of similar size.
- The 2% residue waste is primarily carbon black and ash.
- During the SAIC 3-day review, the processor was fed 121,318 pounds of waste plastic. It produced 10,287 gallons of fuel oil #6 and 4269 gallons of naphtha (Appendix B).
- The actual cost of operating a processor, including utilities, staff and depreciation is $.11 per gallon.
- As unwashed, unsorted waste plastics from industrial sources can be used (i.e. off-spec Crayons), input feedstock costs are primarily preprocessing and transportation.
- In 2010 the plant produced 15,350 gallons of fuel
- In 2011 the plant produced 122,244 gallons of fuel
- In 2012 the plant produced 317,225 gallons of fuel
- The plant has recycled millions of pounds of plastic waste that would otherwise go to landfill.

References


Acknowledgements

Hal Pierce and Dale Kunze of IsleChem, Grand Island NY are greatly appreciated for their assistance in scaling and permitting this process from lab to full scale commercial plant.

Larry Sitzsman, of the NYSDEC is greatly appreciated for seeing the value in the process and writing the letter to start us down this fantastic journey.

Al Carlatti, Mark Hans, and Abbey Snyder of the NYSDEC are greatly appreciated for their support and focus on this project.
The Staff of 20 Iroquois, Niagara Falls, NY who made this possible through persistence, passion, and care for the environment.
Appendix A

Islechem, LLC Validation Report

IsleChem, LLC
Grand Island, NY

April 12, 2010

JBI, Inc retained IsleChem in Dec 2009 to analyze their plastic to oil solution and assist with preparing documentation required for state permits.

We modified JBI's P2O processor to collect data from sensors, residue, and off gas for analysis.

After more than 40 small scale runs of various multicolored mixed plastic feedstocks through the process, and after analyzing the energy consumption, residue, off-gas, and material balance in the process, we have determined:

- JBI's P2O solution is repeatable and scalable.
- Approximately 85-90% of the hydrocarbon composition in the feedstock is converted into a “near diesel” fuel.
- Approximately 8% of the hydrocarbon composition in the feedstock is converted to a usable off gas much like natural gas.
- Approximately 1% of the feedstock remains in the processor as a residue.
- This analyzed residue contains various metals from coloring agents and other plastic additives that were originally in the feedstock plastic and a small amount of carbon.
- The fuel product was analyzed with a gas chromatograph and the chromatogram is similar in many respects to diesel fuel.
- The fuel product viscosity is approximately 2 cst @ 40 degrees C, and is an amber fuel.
- The fuel product contains only trace amounts of sulphur.
- The fuel product centane number exceeds 40.
- The residue does not appear to contain any highly toxic or difficult to dispose of components.
- There is no evidence of air toxins in the emissions.
- The energy balance of the process is positive; that is, more energy value is produced than is consumed by the process. Early data suggests that it is by as much as a factor of two.

Dale R. Kunze
Vice President, Operations
IsleChem, LLC
Appendix B

SAIC Executive Summary

Executive Summary

SAIC Energy, Environment & Infrastructure, LLC ("SAIC"), formerly R. W. Beck, Inc., was retained by JBI, Inc. ("JBI") to review and analyze JBI's Plastic 2 Oil technology (herein, the "Plastic2Oil technology"). JBI agreed that we would conduct our work and review of the Plastic2Oil technology from the perspective of an "Independent Engineer" for a project investor, who might be choosing to invest in a new, prospective project located in Jacksonville, Florida using the Plastic2Oil technology. The end result of our work is a White Paper, which can be obtained through requests to JBI.

To review the Plastic2Oil technology, we visited JBI's Operating Facility (the "Facility") in Niagara Falls, New York during April 25, 2012 to April 27, 2012. We observed the unit while in operation, reviewed historical operating data and permits, and monitored the setup and operation of a controlled performance trial (the "Trial"). Here is a summary of our analysis:

- Unit operated as intended for a continuous 3-day operating period.

- During this period, the unit processed 121,318 pounds of waste plastic feedstock and produced 10,287 and 4,289 gallons of fuel oil no. 6 and naphtha, respectively. The Trial resulted in a yield of approximately 80 percent or 80 pounds of liquid fuel and oil for every 100 pounds of waste plastic feed. Performance metrics from June 14, 2011 to December 21, 2011 indicate an average yield of approximately 86 percent for historical production.

- Fuel samples of the fuel oil and naphtha were collected during the Trial and tested in the on-site lab for flash point, sulfur and silicon and were found to be within ASTM specifications for the fuel oil.

- The proposed system uptime of 75 percent to account for planned and unplanned system outages are reasonable, though uptime will likely be only 50 percent for the first few months after the beginning of commercial operations.

- We only witnessed the processor running at 2,000 pounds per hour due to permitting constraints; however, a 4,000 pound per hour rate appears to be achievable.

We also prepared an "order of magnitude" capital cost estimate for the proposed Commercial Facility at Jacksonville, Florida based on preliminary lay out done by JBI's engineer. We estimate a site consisting of three processors to cost $6.5 million plus the engineering design fees and Contractor Distributable Costs that could add up to $2 million to the overall Capital Cost to construct. Based on the assumptions discussed in our White Paper we expect the Commercial Facility to generate an average EBITDA of $28.0 million per year assuming 75-percent uptime and an 80-percent yield. In a case where the the yield is 40 percent and uptime is 75 percent, the estimated average EBITDA is approximately $13.4 million per year. In a case where the yield is 80 percent and uptime is 50 percent, the estimated average EBITDA is approximately $18.5 million per year.

A fulsome review of the Plastic2Oil technology; testing and verification; performance characteristics; key features, and status of the Plastic2Oil technology implementation and the Jacksonville, Florida Commercial Facility; and our conclusions are included in our White Paper.

SAIC