

Peenemunde and JPL

Von Braun started work on his PhD thesis (rocket combustion processes) in November 1932. All of his experimental work was done at Kummersdorf-West, an artillery range near Berlin—and the Reichswehr paid the freight, and built up a rocket establishment around him. When he got his degree, in 1937, he was made the technical director of the organization, which was soon moved to Peenemunde. There the A-4, better known by its propaganda name “V-2” was designed and developed.

Very little propellant development was involved in the A-4. From the beginning, liquid oxygen was the intended oxidizer, and 70-30 alcohol-water mixture (as had been used by the VFR) the fuel. And Helmuth Walter’s 80 percent hydrogen peroxide was used to drive the fuel pumps. The peroxide entered a decomposition chamber, where it was mixed with a small quantity of a solution of calcium permanganate in water. This catalyzed its decomposition into oxygen and superheated steam, which drove the turbines which drove the pumps which forced the oxygen and the alcohol into the main combustion chamber.

The A-4 was a long range strategic weapon, not designed to be fired at a moment’s notice. It was perfectly practical to set it up, and then load it with alcohol and oxygen just before firing. But the Reichswehr needed antiaircraft rockets that were always ready to fire. When you get word from your forward observers that the bombers are on the way, you don’t have time to load up a missile with liquid oxygen. What you need is a storable propellant—one

that can be loaded into the tanks beforehand – and kept there until you push the button. You can't do that with oxygen, which cannot be kept liquid above -119°C , its critical temperature, by any pressure whatsoever.

The Reichswehr was rather slow to realize the need for AA rockets – maybe they believed Hermann Goering when he boasted, “If the British ever bomb Berlin, you can call me Meyer!” – but when they did they found that work on storable propellants was well under way. It was, at first, concentrated at Helmuth Walter's Witte Werke at Kiel. As has been mentioned, high strength hydrogen peroxide (80–83 percent) first became available in about 1934, and Walter had fired it as a monopropellant, and the Luftwaffe was immensely interested. Like General Arnold, in the U.S. they could appreciate the fact that a JATO rocket would enable a bomber to take off with a heavier load than it could normally carry, and by February 1937, a Walter hydrogen peroxide JATO had helped a Heinkel Kadett airplane to get off the ground. Later in the year, a rocket powered airplane was flown – again using a hydrogen peroxide motor. The Messerschmitt 163-A interceptor used the same propellant.

But peroxide is not only a monopropellant, it's also a pretty good oxidizer. And Walter worked out a fuel for it that he called “C-Stoff.” (The peroxide itself was called “T-Stoff.”) Hydrazine hydrate, $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$ ignited spontaneously when it came in contact with peroxide (Walter was probably the first propellant man to discover such a phenomenon) and C-Stoff consisted of 30 percent hydrazine hydrate, 57 of methanol, and 13 of water, plus thirty milligrams per liter of copper as potassium cuprocyanide, to act as an ignition and combustion catalyst. The reason for the methanol and the water was the fact that hydrazine hydrate was hard to come by – so hard, in fact, that by the end of the war its percentage in C-Stoff was down to fifteen. The Messerschmitt 163-B interceptor used C-Stoff and T-Stoff.

The next organization to get into the rocket business was the Aeronautical Research Institute at Braunschweig. There, in 1937–38, Dr. Otto Lutz and Dr. Wolfgang C. Noeggerath started to work on the C-Stoff-T-Stoff combination. Next, BMW (Bavarian Motor Works – yes, the people who make the motorcycles) were invited by the Luftwaffe to get into the act. Helmut Philip von Zborowski, the nephew of the famous pre-World War 1 racing driver, was in charge of the operation, and Heinz Mueller was his second. In the summer of 1939 BMW got a contract to develop a JATO unit, using the C-T-Stoff combination, and they worked with it for some months. But von Zborowski was convinced that 98 percent nitric acid was the better oxi-

dizer, as well as being immensely easier to get (I.G. Farben guaranteed unlimited quantities), and set out to convert the brass to his point of view. From the beginning of 1940, he and Mueller worked on the nitric acid-methanol combination, and in 1941 proved his point, convincingly, with a perfect thirty-second run at the three thousand pounds force thrust level. He even convinced Eugen Sänger, who was sure that oxygen was the only oxidizer worth thinking about.

And in the meantime, early in 1940, he and Mueller had made an immensely important discovery—that certain fuels (aniline and turpentine were the first they found) ignited spontaneously upon contact with nitric acid. Noeggerath learned of this, and joined the BMW people in their search for fuels with this interesting property. His code name for nitric acid was “Ignol” and for his fuels “Ergol,” and, a fast man with a Greek root, he came up with “Hypergol” for the spontaneous igniters. “Hypergol” and its derivatives, such as the adjective “hypergolic” have become a permanent part not only of the German, but of the English language, and even, in spite of the efforts of Charles de Gaulle to keep the language “pure,” of the French as well.

The discovery of hypergolicity was of major importance. Running a rocket motor is relatively easy. Shutting it down without blowing something up is harder. But starting it up without disaster is a real problem. Sometimes electrical igniters are used—sometimes pyrotechnic devices. But neither can always be trusted, and either is a nuisance, an added complication, when you already have more complications than you want. Obviously, if your combination is hypergolic, you can throw out all the ignition schemes and devices, and let the chemistry do the work. The whole business is much simpler and more reliable.

But as usual, there’s a catch. If your propellants flow into the chamber and ignite immediately, you’re in business. But if they flow in, collect in a puddle, and *then* ignite, you have an explosion which generally demolishes the engine and its immediate surroundings. The accepted euphemism for this sequence of events is a “hard start.” Thus, a hypergolic combustion must be *very* fast, or it is worse than useless. The Germans set an upper limit of 50 milliseconds on the ignition delay that they could tolerate.

Incidentally, and to keep the record straight, Zborowski named *his* propellants after plants. Nitric acid he called “Salbei” for sage, and his fuels “Tonka,” after the bean from which coumarin, which smells like vanilla, is extracted. Considering the odors of the things he worked with, I can’t think of more inappropriate names!

The first ignition delay tests were, to put it mildly, somewhat primitive. After a long night session, searching through old chemistry texts for substances that were violently reactive with nitric acid, Zborowski and Mueller would soak a wiping rag with a promising candidate and spray it with nitric acid and see how quickly – or if – it burst into flames. And they ran into a peculiar phenomenon. An old, used wiping rag from the machine shop would sometimes ignite much faster than a new clean one soaked with the same fuel. Their chemistry laboratory furnished them with the answer. Traces of iron and copper from the shop, as the metals or as salts, catalyzed the ignition reaction. So they modified their 98 percent nitric acid, “Salbei” by adding to it 6 percent of hydrated ferric chloride, and called the new oxidizer “Salbeik.”

The wiping-rag technique was soon supplanted by a somewhat more sophisticated gadget with which you could drop a single drop of a candidate fuel into a thimbleful of acid, and determine its hypergolic properties with less risk of setting fire to the whole shop, and for the next four years BMW on the one hand and Noeggerath on the other were trying the hypergolicity of everything they could lay their hands on. At BMW, where propellant development was directed by Hermann Hemesath, more than 2000 prospective fuels were tried. And very soon the I.G. Farben organization at Ludwigshaven started doing the same thing. With a deplorable lack of imagination, Farben eschewed code names at first, and labeled their mixtures with code numbers like T93/4411.

The fuels that the three organizations developed were many and various, but at the same time very much alike, since there was a limited number of compounds which were hypergolic with nitric acid – and available in any quantity. Tertiary amines, such as triethyl amine were hypergolic, and aromatic amines, such as aniline, toluidine, xylidine, N methyl aniline were even more so. Most of the mixtures tried – neat fuels consisting of a single pure compound were unheard of – were based on the aniline family, frequently with the addition of triethylamine, plus, at times, things like xylene, benzene, gasoline, tetrahydrofuran, pyrocatechol, and occasionally other aliphatic amines. The BMW Tonka 250 comprised 57 percent of raw xylidine and 43 of triethylamine (it was used in the “Taifun” missile) and Tonka 500 contained toluidine, triethylamine, aniline, gasoline, benzene, and raw xylidine. Noeggerath added furfuryl alcohol to Tonka 250 to get “Ergol-60” which he considered the “best” hypergol, and reported, somewhat wistfully, that furfuryl alcohol was readily available in the United States – as it was not in Germany.

As soon as one of the investigators found a mixture that he liked he applied for a patent on it. (Such an application would probably not even be considered under the much stricter U.S. patent laws.) Not surprisingly, everybody and Hemesath and Noeggerath in particular, was soon accusing everybody else of stealing his patent. In 1946, when Heinz Mueller came to this country, he met Noeggerath again, and found him still indignant, bursting out with "And BMW, especially Hemesath, did *swipe* a lot of patents from us!"

Around 1942 or 1943 I.G. Farben shifted the emphasis of their fuel work away from the mixtures they had been working with at first, and which were so similar to the Tonkas and the Ergols, to a series of fuels based on the "Visols," which were vinyl ethers. The vinyl ethers were very rapidly hypergolic with MS-10, a mixed acid consisting of 10 percent sulfuric acid and 90 percent nitric, and the ignition delay was less sensitive to temperature than it was with straight nitric. (This had been a serious problem. A propellant pair might ignite in 50 milliseconds at room temperature, and wait around a whole second at 40 below.) Also, it was believed, practically as an article of faith, that MS-10 did not corrode stainless steel. This was a delusion that lasted five years before it was punctured.

A typical mixture, patented by Dr. Heller in 1943, consisted of 57.5 percent Visol-1 (vinylbutyl ether) or Visol-6 (vinylethyl ether) 25.8 percent Visol-4 (divinylbutanediolether) 15 percent aniline, and 1.7 percent of iron pentacarbonyl or iron naphthenate. (Heller had to put his iron catalyst in his fuel rather than in his oxidizer, since the latter contained sulfuric acid, and iron sulfates are insoluble in nitric acid.) There were many variations on these fuels, vinylisobutyl ether being substituted at times for the n-butyl compound. All in all, more than 200 mixtures were tried, of which less than ten were found satisfactory. "Optolin" was a mixture of aniline, a Visol, aromatics, sometimes amines, gasoline, and pyrocatechol. The Wasserfall SAM used a Visol fuel.

Several agencies tried to discover additives which, in small quantities, would make gasoline or benzene or methanol hypergolic with acid. Things like iron carbonyl and sodium selenide were more or less successful, but the success was academic at best, since the useful additives were all either too rare, too expensive, or too active to live with.

But nitric acid was definitely the winner. Many German missiles were designed, at first, to use peroxide, but as the war went on, the Walter Type XVII submarines threatened to use up the whole production, and as the nitric acid work was so successful, the shift to the

latter oxidizer for missile work was inevitable. During this period many other combinations than those actually tried were considered, and theoretical performances were calculated. These calculations were not the early naïve estimates of Sänger et al., but considered the combustion pressure, the exhaust pressure, thermal efficiency, temperature of combustion, dissociation—the whole business. Such exact calculations are outrageously tedious—a single one done with a desk calculator, can easily take a whole day. But Dr. Grete Range and others struggled through them, considering as fuels, alcohol, alcohol-water, gasoline, diesel fuel, ammonia, propargyl alcohol, and God only knows what else, and as oxidizers, oxygen, nitric acid, N_2O_4 , tetranitromethane, ozone, and OF_2 , although the laboratory men were never able to lay their hands on enough of the last to characterize it. And as early as 1943 they were thinking of using chlorine trifluoride, which before that had been nothing but a laboratory curiosity. But it had recently been put into production—its intended use was an incendiary agent—and they calculated its performance too, with ammonia and with such oddities as a suspension of carbon in water.

One calculation made at this time by Dr. Noeggerath, showed that if the propellants in the A-4 were replaced by nitric acid and diesel fuel, the range of the missile would be increased by an appreciable percentage—not because their propellants had a better performance than the oxygen-alcohol combination actually used, which they did not, but because their higher density allowed more propellant to be stuffed into the tanks. This calculation had no particular effect at that time, although the A-10, a planned successor to the A-4, was to have used the new combination, but some years later, in Russia, the consequences were to be hilarious.

The oxidizer that was always a “might have been” was tetranitromethane. It’s a good oxidizer, with several advantages. It’s storable, has a better performance than nitric acid, and has a rather high density, so you can get a lot of it in a small tank. But it melts at $+14.1^\circ C$ so that at any time other than a balmy summer day it’s frozen solid. And it can explode—as Esnault-Pelterie had discovered, and it took out at least one German laboratory. The eutectic mixture with N_2O_4 , 64 percent TNM, 36 N_2O_4 , doesn’t freeze above $-30^\circ C$, and is considerably less touchy than is straight TNM, but it was still considered dangerous, and Noeggerath refused to have anything to do with it or, even to permit it in his laboratory. But the engineers kept looking at it wistfully, and when they received a (completely false) intelligence report that it was being used on a large scale in the United States, the Germans heroically started synthesis, and had accumulated some eight

or ten tons of the stuff by the end of the war. Nobody ever found any use for it.

Another idea which didn't get anywhere, was that of a heterogeneous fuel—a suspension, or slurry, of a powdered metal, such as aluminum, in a liquid fuel such as gasoline. This had been suggested by several writers, among them Tsander in Russia and Sanger in Austria, and Heinz Mueller of BMW tried it out, using powdered aluminum or magnesium in diesel oil. The performance was very poor—the chamber pressure was 50 to 100 psi instead of the 300 they were shooting for—due to the incomplete combustion of the metal. But the other results were spectacular. The motor was fired in a horizontal position against an inclined wall to deflect the exhaust stream upwards. But the unburned metal particles settled down and decorated all the pine trees in the vicinity with a nice, shiny, silvery coating—very suitable for Christmas trees. The slurry idea was to emerge again twenty years later, to drive another generation of experimenters crazy.

Experimentation on monopropellants (which were called “Monergols”) continued until the end of the war. In 1937–1938 a good deal of work was attempted with solutions of N_2O or NH_4NO_3 in ammonia. (The latter mixture, under the name of Driver's solution, had been known for many years.) The only result of these experiments was a depressing series of explosions and demolished motors. And at Peenemunde, a Dr. Wahrmke tried dissolving alcohol in 80 percent H_2O_2 and then firing *that* in a motor. It detonated, and killed him. The Wm. Schmidding firm, nevertheless, kept on experimenting with a monopropellant they called “Myrol,” an 80–20 mixture of methyl nitrate and methanol—very similar to the nitroglycerine-methanol mixture that Crocco had tried years before. They managed to fire the material, and got a fairly respectable performance, but they were plagued by explosion after explosion, and were never able to make the system reliable.

And there was finally the propellant combination that the BMW people and those at ARIB called the “Lithergols”—which was really a throwback to the original hybrid motor tried by Oberth during the UFA period. Peroxide or nitrous oxide, N_2O , was injected into a motor in which several sticks of porous carbon were secured. Nitrous oxide can decompose exothermically into oxygen and nitrogen, as peroxide does to oxygen and steam, and can thus act as a monopropellant, but the experimenters wanted to get extra energy from the combustion of the carbon by the oxygen formed. When they surrendered to the Americans at the end of the war, they assured their

captors that just a little more engineering work was needed to make the system work properly. Actually some twenty years elapsed before anybody could make a hybrid work.

Meanwhile, back at the ranch—

The most striking thing about propellant research in the United States during the war years is how closely it paralleled that in Germany. True, there was no American A-4, and high strength hydrogen peroxide was unobtainable in this country, but the other developments were closely similar.

As mentioned in the first chapter, GALCIT's first job for the armed forces was to produce a JATO to help the Army Air Corps get its bombers off the ground. And the Air Corps demanded a storable oxidizer—they were not, repeat not, going to fool around with liquid oxygen.

So the first order of business was choosing an oxidizer. Oxygen and ozone, neither of them storable, were obviously out. Chlorine had insufficient energy, and Malina, Parsons, and Forman who, with the assistance of Dr. H. R. Moody, did a survey of the subject, considered that N_2O_4 was impractical. It is difficult to say why, but the extremely poisonous nature of the beast may have had something to do with its rejection. They considered 76 percent perchloric acid, and tetranitromethane, and finally settled on red fuming nitric acid, RFNA, containing 6 or 7 percent N_2O_4 . They tried crucible burning of various fuels with this acid—gasoline, petroleum ether, kerosene, methyl and ethyl alcohol, turpentine, linseed oil, benzene, and so on, and found that the acid would support combustion. Further, they found that hydrazine hydrate and benzene were hypergolic with it, although they had never heard of the word, so acid it was. There is a highly nonprophetic statement in the final Report for 1939–1940, Air Corps Jet Propulsion Research, GALCIT—JPL Report No. 3, 1940. (By now Malina's group had become the Jet Propulsion Laboratory, with von Kármán at the head.)

“The only possible source of trouble connected with the acid is its corrosive nature, which can be overcome by the use of corrosion-resistant materials.” Ha! If they had known the trouble that nitric acid was to cause before it was finally domesticated, the authors would probably have stepped out of the lab and shot themselves.

Be that as it may, the report was an excellent survey of the field as it was at that time, and contained sophisticated and accurate performance calculations. The procedure had been developed in Malina's 1940 PhD thesis, and was essentially and inevitably the same as that developed in Germany. One of the first compilations of the thermo-

dynamic properties of exhaust gases was published by J. O. Hirschfelder in November 1942, as necessary raw data for such computations.

Malina and company started experimental work with RFNA and gasoline as early as 1941—and immediately ran into trouble. This is an extraordinarily recalcitrant combination, beautifully designed to drive any experimenter out of his mind. In the first place, it's almost impossible to get it started. JPL was using a spark plug for ignition, and more often than not, getting an explosion rather than the smooth start that they were looking for. And when they did get it going, the motor would cough, chug, scream and hiccup—and then usually blow anyway. Metallic sodium suspended in the fuel helped the ignition somewhat, and benzene was a little better than gasoline—but not much, or enough. It took an accidental discovery from the other side of the country to solve their immediate problems.

Here we must backtrack. From 1936 to 1939, Robert C. Truax, then a midshipman at the U.S. Naval Academy, had been experimenting with liquid fueled rockets, on his own time and with scrounged material. He graduated, spent the required two years on sea duty, and in 1941, then a lieutenant commander, was ordered to the Engineering Experiment Station at Annapolis, with orders to develop a JATO. For the Navy was having trouble getting their underpowered and overloaded PBM and PBY patrol bombers off the water. And he, too, ran into ignition and combustion difficulties. But one of his small staff, Ensign Stiff, while working on gas generators (small combustion devices designed to supply hot gas under pressure) discovered that aniline and RFNA ignited automatically upon contact. (Such discoveries are usually surprising, not to say disconcerting, and one wonders whether or not Ensign Stiff retained his eyebrows.)

At any rate, Frank Malina, visiting EES in February of 1942, learned of this discovery, and instantly phoned JPL in Pasadena; and JPL immediately switched from gasoline to aniline. And their immediate difficulties miraculously disappeared. Ignition was spontaneous and immediate, and combustion was smooth. They had a 1000-pound thrust motor running by the first of April (these people were professionals by that time) and on the fifteenth it boosted an A20-A medium bomber into the air—the first flight of a liquid JATO in the United States.

Truax, of course, adopted the propellant combination, and early in 1943, hanging two 1500 pound units on a PBY, managed to get the much overloaded Dumbo off the water.

Other people were working on JATO's for the Navy, among them Professor Goddard himself, whose unit was successfully flown in a

PBY in September 1942—the first Navy JATO. He used his classic combination of liquid oxygen and gasoline, but Reaction Motors, also active in the field, came up with an ingenious variation.

Reaction Motors, Inc., generally called RMI, was founded in 1941 by a handful of veterans of the Americal Rocket Society including James Wyld, Lovell Lawrence, and John Shesta, and undertook to build a JATO unit. They first used liquid oxygen—all the ARS work had been with that oxidizer—and gasoline. But they found that the combination was too hot, and burned out their motors. So, as the gasoline entered the chamber, they mixed it with water through a metering valve. Combustion was smoother, and the motor stayed in one piece. This was a somewhat less elegant solution to the problem of combustion temperatures than was that used by the VFR (and Peenemunde) when they mixed water with their alcohol fuel. The RMI unit was successfully flown in the PBM in 1943. During the trials, run on the Severn River, the exhaust jet set the tail of the seaplane on fire, but the test pilot rose (or sank) to the occasion and set the plane down, tail first on the water in the manner of an old time movie comedian with his coattails on fire, seating himself hurriedly in a washtub full of water, with appropriate hissing noises and clouds of steam.

The aniline-RFNA combination had the one—but magnificent—virtue that it worked. Otherwise it was an abomination. In the first place, aniline is much harder to come by than gasoline—particularly in the midst of a dress-shirt war, when everybody and his brother wants to use it for explosives and what not. Second, it is extremely poisonous, and is rapidly absorbed through the skin. And third, it freezes at -6.2°C , and hence is strictly a warm-weather fuel. The Army and the Navy both, in a rare example of unanimity, screamed at the thought of using it. But they had no choice.

Two closely interwound lines of research characterize the rest of the war period. One was designed to reduce the freezing point of aniline, the other was to make gasoline, somehow, hypergolic with nitric acid. American Cyanamid was given a contract to investigate additives which might have the latter effect and JPL worked both sides of the street, as well as experimenting with changes in the composition of the acid. Besides their usual RFNA, containing about 6 percent N_2O_4 , they experimented with one containing about 13 percent, as well as with a mixed acid rather similar to that the Germans were using, but a little more potent. One mixture they used contained 88 percent nitric acid, 9.6 percent sulfuric, and 2.4 percent SO_3 . (This was very similar to the mixed acids used in explosives manufacture.) And they, too, believed that it didn't corrode stainless steel.

The obvious way to lower the freezing point of aniline is to mix it with something else – preferably something that is as hypergolic as the aniline itself. And the obvious way to make gasoline hypergolic is to mix *it* with something that is. Both lines of endeavor were pursued with enthusiasm.

At LPL they mixed aniline with orthotoluidine, its near relative, and got a eutectic freezing at -32°C . But *o*-toluidine was as scarce as aniline, and although the mixture was successfully fired, it never became operational. A more practical additive was furfuryl alcohol, for which Zborowski was pining. Furfuryl alcohol comes from oat hulls and Quaker Oats had tank cars of the stuff, which they were delighted to sell to anybody who would take it off their hands. And 20 percent of furfuryl alcohol in aniline reduced the freezing point to 0°F , or -17.8°C , and the eutectic mixture, 51 percent aniline, 49 furfuryl alcohol, had a freezing point of -42°C . And furfuryl alcohol itself was about as hypergolic as aniline.

And to gasoline, JPL added aniline, diphenylamine, mixed xylidines and other relatives of aniline; assorted aliphatic amines, and everything else they could think of, and then measured the ignition delay. But they never found an additive which, in small percentages, would make gasoline rapidly hypergolic, with either RFNA or mixed acid. One of their best additives was mixed xylidines, but it took about 50 percent of the xylidines in the mixture to make it reliably and rapidly hypergolic – which took it out of the additives class, and made it a major component. To make it more discouraging, there were no production facilities for the xylidines in the United States, and although Aerojet looked at a similar mixture a few years later (in 1949) it never came to anything.

American Cyanamid was having a similar experience. They started with #2 fuel oil, diesel oil, and gasoline, and added to the particular fuel aniline, dimethylaniline, mono- and diethylaniline, crude monoethylaniline – and turpentine. Most of their work was done with mixed acid, a little with RFNA, and some with straight 98 percent nitric acid (White Fuming Nitric Acid, or WFNA). And in no case did they find an effective additive. But they found that turpentine was magnificently hypergolic with mixed acid or RFNA, and might well be a good fuel all by itself. (And think of all those lovely votes from the piney woods of the South!)

Aerojet Engineering was founded in March of 1942, to act, essentially, as the manufacturing arm of JPL. The founders were von Kármán, Malina, Parsons, Summerfield, and Forman, all of JPL, plus Andrew Haley, who was von Kármán's attorney. And they started

their own propellant research program, although for some years it was difficult to disentangle it from JPL's.

Aerojet was the first organization to work extensively with crude N-ethyl aniline, sometimes called monoethylaniline, as a fuel. This is almost as rapidly hypergolic as aniline. The crude or commercial product contains about 10 percent diethylaniline and 26 straight aniline, the remainder being the monoethyl compound, and its freezing point is about -63°C . All in all, it was an elegant answer to the freezing point problem, but it was just about as poisonous as its ancestor, and just as hard to come by.

But it could be lived with. The propellants for the Aerojet JATO, in production by the end of the war, were mixed acid and monoethylaniline, as were those of RMI's motor for the Navy's surface-to-air missile, Lark, whose development started in 1944. The surface-to-surface Corporal, started the same year, was designed around the RFNA-aniline-furfuryl alcohol combination.

Three organizations worked on monopropellants during the war although the effort was limited. All of them concentrated on nitromethane. JPL worked on it first, in 1944, or earlier, and found that its combustion was improved by the addition of small quantities of chromium trioxide (later chromium acetylacetonate) to the fuel. Aerojet also worked with it, and found that it was necessary to desensitize it by the addition of 8 percent of butyl alcohol. And Bob Truax, at EES, tried his hand – and was almost killed when somebody connected the wrong pipe to the right valve and the tank blew. And finally Dave Altman, at JPL, tried a mixture of benzene and tetranitromethane, which naturally detonated at once.

And then the war was over, and the German work came to light – and things started to get really complicated.