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SPACE TOOL POWER SOURCE SAFETY AND RELIABILITY INVESTIGATION

By Manufacturing Research and Technology Division
Manufacturing Engineering Laboratory

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Huntsville, Alabama

ABSTRACT

An investigation comparing energy media for use with power tools in a space environment is presented. The tools will be used in space for operations such as manufacture, assembly, maintenance, and emergency repair. The criteria for this study are safety and reliability of gas, electric and hydraulic power systems. The potential hazard of each energy medium is discussed separately. The hydraulic power system presents a major fire hazard. The gas power system may produce toxicants if exhaust gases are expelled in the spacecraft environment. The electric power system may create ozone, a toxic gas, particularly when brush arcing takes place. One recommendation is to use a brushless dc power system using a solid state electronic switching system to replace the brush-commutated dc motor, thereby eliminating brush arcing.

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MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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INTRODUCTION

A previous study compared various space tool power sources with respect to power/mass requirements.* This report presents the results of a continuing study directed primarily at the safety and reliability of the possible power sources to be used as a multi-purpose driving unit for hand-operated tools.

The potential power sources are divided into two basic safety groups, those involving fuels and/or power cycles which are normally considered to be inherently extra-hazardous and those involving fuels and/or power cycles which are normally considered to be of low inherent hazard. Other areas of discussion included in this report are:

1. Safety considerations for gas, electric, and hydraulic power.
2. Fire and blast hazards.
3. Toxicological hazard.
4. Special tool hazards.

Conclusions with recommendations are drawn as to the safest and most reliable power source for space use.

INITIAL SELECTION

All the potential power sources can easily be placed initially into two basic safety groupings.

1. Those power sources involving fuels and/or power cycles which are normally considered to be inherently extra-hazardous.

2. Those power sources involving fuels and/or power cycles which are normally considered to be of low inherent hazard.

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* Space Tool Power Source Investigation. Internal Note R-ME-67-4.

The inherently extra-hazardous class includes all the solid and liquid rocket propellant-oxidizer combinations and the monopropellants such as hydrazine and hydrogen peroxide.

These high energy materials are inherently hazardous since they are highly reactive, frequently unstable, and relatively toxic with very low threshold limit values (TLV). Low allowable concentration percentages apply to these materials as separately stored fuel or oxidizer components and as reaction products. Their maximum allowable concentrations (MAC) from a flammability-limit standpoint are also low. As highly reactive agents they may be ignited by low-energy ignition sources; some are hypergolic. They usually combine or disassociate at high temperatures; therefore, the reaction chambers, and frequently the exhaust products, must be carefully and completely isolated from astronaut proximity. These extra-hazardous power sources have been developed for specialzed space use and previously have been used on manned space flights. However, the location requirements for thrust engines, spacecraft attitude controllers, extravehicular activity (EVA) maneuvering units, and other special uses are much less severe than the location and use requirements placed on the space tool power source.

It is possible that this category of power source could qualify for specialized EVA such as a high power/mass emergency tool [1]. However, as long as the power source may be used within the cabin, these extra-hazardous systems should be eliminated from the candidate list. This conclusion and the considerations in arriving at it are in agreement with that proposed by Roth [2].

The initial selection leaves as potentially useable power sources only the normally low-hazard power systems. This category includes gas (air) powered, electric powered, and hydraulic power systems [3]. All three of these systems are used on Earth as tool power sources.

Several previous space tool power sources have used dc electric motors [4,5]. The characteristics of this type electric motor are very favorable for use as a tool power source. The dc electric motor's high efficiency, high power-to-weight ratio, and torque/load characteristics make it one of the most suitable electric motors for hand tool use. In addition, spacecraft electric power systems usually include several dc prime power sources. This is true because of the basic dc nature of these devices, i.e., solar cells, thermoelectric, batteries, and/or fuel cells. The dc motor is a natural choice since it can use power directly from these prime spacecraft power sources.

Previous considerations have eliminated all the exotic high-energy gas cycles. This leaves the low-energy, pressure-work type gas cycle as used in all terrestrial gas (air) powered hand tools. These motors use air at line pressure developing power across a work-surface area; little or no work is obtained by gas expansion and the gas reaches the exhaust port at practically line pressure.

True turbine motors do not operate well on this power source [6]. They have even lower starting torques than turbine motors operating on more effective turbine power cycles. Except for very specialized light loads, high-speed gas-powered turbines are not considered to be valuable as a space power system. Only two types, the piston and the rotating vane, remain as of major importance. The piston motor is generally heavier and bulkier, and is usually not offered in tools under 373 W to 559 W (0.5 to 0.75 hp). The vane-type gas pressure motor will be the major gas motor considered in this report.

In the early stages of investigating the safety aspects of pneumatic power sources it was felt that a closed fluid working cycle might offer several safety advantages over the pneumatic. Therefore the safety aspects of hydraulic tool power will also be considered.

Hydraulic systems are mainly power transmission devices and are not prime power sources. The hydraulic system will have to be driven by a gas or electric prime power source and it will have some of the advantages and disadvantages associated with the chosen prime power source.

SAFETY CONSIDERATIONS FOR GAS, ELECTRIC, AND HYDRAULIC POWER

Even though the three remaining candidate power systems are considered safe in normal terrestrial use, their use in space flight poses several unusual problems of some potential danger. These specialized problems can be reduced to three categories:

1. Fire and blast.

2. Toxicological contamination.

3. Safety hazards peculiar to the type of tool.

The three types of power sources will now be considered within these three potential hazard areas.

FIRE AND BLAST

Two very different use environments apply to the proposed tool power source, EVA or intravehicular activity (IVA). In EVA use, the accidental fire or blast hazard is much reduced from that found for similar tools in terrestrial use [2, 7]. This is primarily a result of the unavailability of a natural supply of oxygen in the space vacuum environment. Most liquid or gaseous fuels or oxidizers will be vented naturally and dispersed by this very low pressure. Also, a decrease in pressure usually narrows the flammability range and increases the auto-ignition temperature [8].

Another factor which will reduce the chance of orbital EVA fire is the unusual "zero-gravity" gravitation field. Zero gravity, in the absence of induced relative velocities, will reduce the mixing process to either a random low-velocity mixing or diffusion-controlled mixing. Either process is less effective than mixing driven by displacement convection between "heavier and lighter" liquids and gases.

The normal terrestrial convection-burning process can also be affected by zero gravity. Spalding lists the equation for the burning of fuel vapor droplets in air [9].

$$\frac{Mdc}{k} = (45B)\ 0.75 \left[\frac{(gd^3)^{0.25}}{\alpha}\right]$$

where M = Vaporization rate per unit face area.

d = Droplet sphere diameter

c = Specific heat

k = Thermal conductivity

B = Transfer number, a fuel function

g = Acceleration due to gravity

α = Thermal diffusivity

Even though the equation indicates so, the conclusion obviously cannot be made that the burning rate is zero when g is zero. Roth suggests an equation of the form [2]

$$M_g = M_o \, [1 + f\,(g)]$$

The function f (g) would be relatively small compared with unity, and the subscripts g and o refer to gravity and zero-gravity cases. In any case the lack of normal convection current per se will reduce the major natural oxygen replenishment mechanism found operating in an Earth atmosphere (convective) fire.

The extravehicular environment is considered by most authors as a natural fire extinguisher for fires that may break out even inside the cabin. The procedure suggested is to depressurize the cabin to the exterior vacuum in case of internal cabin fire.

It has been shown that fire hazards increase in space flight; therefore, the major increased fire hazard in space flight must arise from the special conditions of IVA and not EVA.

Several extensive studies have been accomplished aimed at defining the extra hazards introduced within the space cabin in space flight. Final and exact answers to these questions must await combustion experiments scheduled for future flights. It is known that past flights with 100 percent oxygen cabin atmospheres were relatively more hazardous than an Earth environment. Not only may more oxygen be available but the lack of a diluent atmospheric gas also contributes to the shortened time scale and higher temperature of combustion found in cabin fires under 100 percent oxygen atmospheres.

No attempt will be made here to reassess or restate these extensive studies except to accept the environment as a potentially more positive fire risk and to reference prior test data as it specifically applies to operation of or to materials of construction of the space tool power source.

The Power Tool as an Ignition Source

All power tools have certain common potentials as ignition sources. In this function the tool would serve to ignite another fuel or combustible.

This is the major terrestrial danger considered for constructing and using nonsparking tools in highly combustible or explosive atmospheres. The problem may be more severe in space cabin atmospheres. Minimum ignition energies are lowered with increased oxygen partial pressure [10]. Huggett et al. showed slightly lower ignition energies for some common materials required in space cabin atmospheres as compared to ignition in air [11].

According to Voigtsberger [12] and Roth [2] the spark energies required to ignite common clothing materials may be decreased more than one thousand fold in pure oxygen to levels similar to those of electrostatic sparks from the human frame. The rate of burning after ignition of some common space cabin materials may increase by five fold on replacing air with oxygen. Propagation of flame may be much faster in the gas phase [13]. There are certain ignition source modes which are common to every tool regardless of the type of power source. These are discussed in the paragraphs below.

Electrostatic Sparks. In general, the grounded all-metal tool housing would not be expected to build up or hold an electrostatic charge in normal use. Electrostatic spark potentials can be accumulated only on parts of a device which remain electrically isolated for a sufficient period. Under certain conditions aluminum alloy housings, as might be used in all types of tool housing, could become electrostatically dangerous.

Aluminum is a chemically reactive material, especially with respect to its combination with oxygen. The aluminum oxide product is highly adherent to the base aluminum, is chemically inert, hard, dense, mechanically strong, and serves to protect the base aluminum from further oxidation and other chemical attack. Aluminum oxide is also a dielectric material. Its formation on the aluminum surface, especially under dry atmosphere conditions, can create an electrically isolated surface which could store an electrostatic charge.

Frequently aluminum products are processed through one of the anodizing processes. Anodizing processes control the formation of aluminum oxide on the aluminum surface; usually it is done to give the surface a harder, more wear resistant finish of from 25 to 26 μm (1 to 3 mils) thickness. The "hard coat" process is a special anodizing process which gives a surface from 177.8 to 304.8 μm (7 to 12 mils) or more and is especially long-wearing and abrasion-resistant.

Such coatings pose a hazard and should be avoided to reduce the electrostatic spark hazard from aluminum surfaces. Further, should aluminum be preferred because of its other properties to another nonsparking alloy, such as beryllium-copper, which does not exhibit the tendency to auto-oxidize to a dielectric surface, then special surface finishes should be developed for the aluminum housing. Such surface finishes would coat the aluminum with a thin, conductive, nonsparking, non-auto-oxidizing material. Care must be taken in such a coating process to insure that the coating is applied directly on the aluminum base metal. An equally dangerous capacitive spark source can be created should a conductive coating be placed over the aluminum oxide coating.

The vane air tool has another type potential electrostatic hazard. The rotating vanes themselves are usually manufactured of phenolic-impregnated linen-fiber material. This material can generate electrostatic sparks which would discharge vane-to-housing. The high moisture conditions of most delivery air in terrestrial maintenance shops would serve to reduce or eliminate such a condition here on Earth. In a dry atmosphere the high rotational speed might help compensate for the low insulated surface (vane) area and an electrostatic spark hazard would exist within the air tool. Development of conductive vane materials or conductive surface coatings would eliminate this hazard in the air tool.

Switch Sparks. The electric motor as a primary space tool power source, or as the power drive in a hydraulic system, would have whatever ignition hazard is offered by sparking at an on-off motor switch. The gas power source does not offer this particular hazard. By definition such sparking can occur only between the contact points in the switch. The problem of the ejecta-spark, or ejected hot particle, as an ignition source is treated separately in this report. The physical arrangement of such electrodes is such that the practical danger of a fire being initiated by this spark is offered only to ignite that fuel supply which can be brought to the spark, i.e., passed between the electrodes. Gaseous fuel-oxidizer mixes meet this requirement and will be treated as the only probable fire threat offered by the switch spark. The major space flight atmospheric variables of the type of gaseous composition, the percentage of oxygen, and the total pressure affect both the minimum electric gap length required to ignite a given gaseous fuel-oxygen mix and also the minimum voltage for the production of the spark [11, 14, 15].

Short-time sparks supply the energy necessary for ignition in a few microseconds. This energy triggers the chemical reaction (flame) in a very small sphere of the combustible mixture. For some time it has been known that continuation of the flame front and development of a general fire will depend on whether the small initial sphere can propagate without being extinguished [2]. The electrode gap may act as a quenching agent on this small flame. Figure 1 shows the dependence of the critical (minimum) energy for ignition on the gap length.

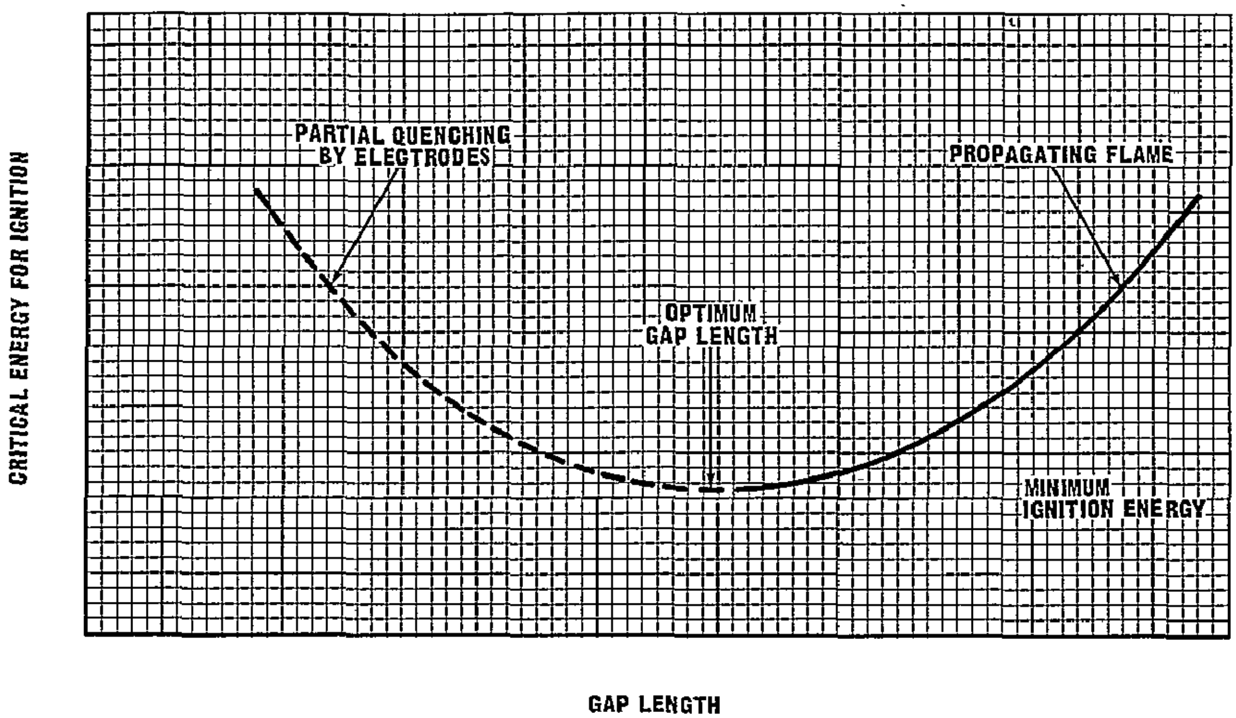


FIGURE 1. MINIMUM IGNITION ENERGY VERSUS GAP LENGTH

From this graph it can be seen that gap lengths shorter than the minimum will require greater spark energies to propagate combustion. A spark gap will begin to dissipate its energy almost immediately in the case of "break" sparks, the left hand branch of the curve. In this case the close spacing of the operating contacts may serve to quench the process. This indicates that "make" sparks will be more dangerous than "break" sparks. There are other factors operating in break sparks in motor circuits, however, which makes the energy available in motor circuit "break" sparks more than that energy available to the switch in "make" sparks. These effects will be considered later.

The minimum ignition energy also depends on the fuel-air ratio for any given combustible mixture (Fig. 2).

The relative diffusivity of the fuel is also a control on the minimum ignition energy. For a homologous series of hydrocarbon fuels the minimum iginition energy shifts toward higher stoichiometric fuel-air ratios.

A practical demonstration of the wide variation of minimum ignition-gap length on oxygen concentration for two common gaseous hydrocarbon fuels (gasoline and ethyl ether) is shown in Figure 3. As the percentage of oxygen in the air is varied from 20 to 75 percent, the minimum spark gap for ignition of gasoline decreases from 0.089 mm down to 0.001 mm. These test results show the minimum spark gap required to ignite a gaseous fuel at atmospheric pressure decreases by a factor of more than 10 when the oxygen concentration is increased from 20 percent to above 75 percent.

Figure 4 shows the effective increase of the fire-ignition hazard with increasing oxygen concentration. It decreases with decreasing total pressure. From atmospheric pressure 101.35×10^3 N/m^2 absolute (14.7 psia) down to 19.99×10^3 N/m^2 absolute (2.9 psia) the minimum ignition energy decreases by a factor of 10.

The data of Figures 3, 5, and 6 taken together indicate that in the current space cabin atmosphere and those found on projects Mercury and Gemini, the overall result of increasing the oxygen concentration to 100 percent and decreasing the total pressure to 24.13×10^3 to 37.92×10^3 N/m^2 absolute (2.5 to 5.5 psia), decreases the minimum spark ignition energy by an overall factor of 12 to 70.

In considering the development of sparks at switch contacts there are two separate and different conditions: The "make" spark and the "break" spark. The "make" spark, or breakdown potential, V_b, is a function of the type gas and the product, δS, where δ is the density of the gas and S the gap width. Considering the temperature to be constant, we may replace this product with pS, where p is atmospheric (or space cabin) pressure and S is electrode gap width. This similitude law is known as Paschen's law. Figure 6 shows a plot of V_b versus the product pS.

The minimum breakdown voltage of 330 volts, occurs at pS = 9.117 N/m^2-cm (2×10^{-3} atm-cm). This general curve of Paschen has been reproduced by the data of more recent investigators [16]. Recently Germer [17-19] investigated very closely spaced electrodes down to a spacing of

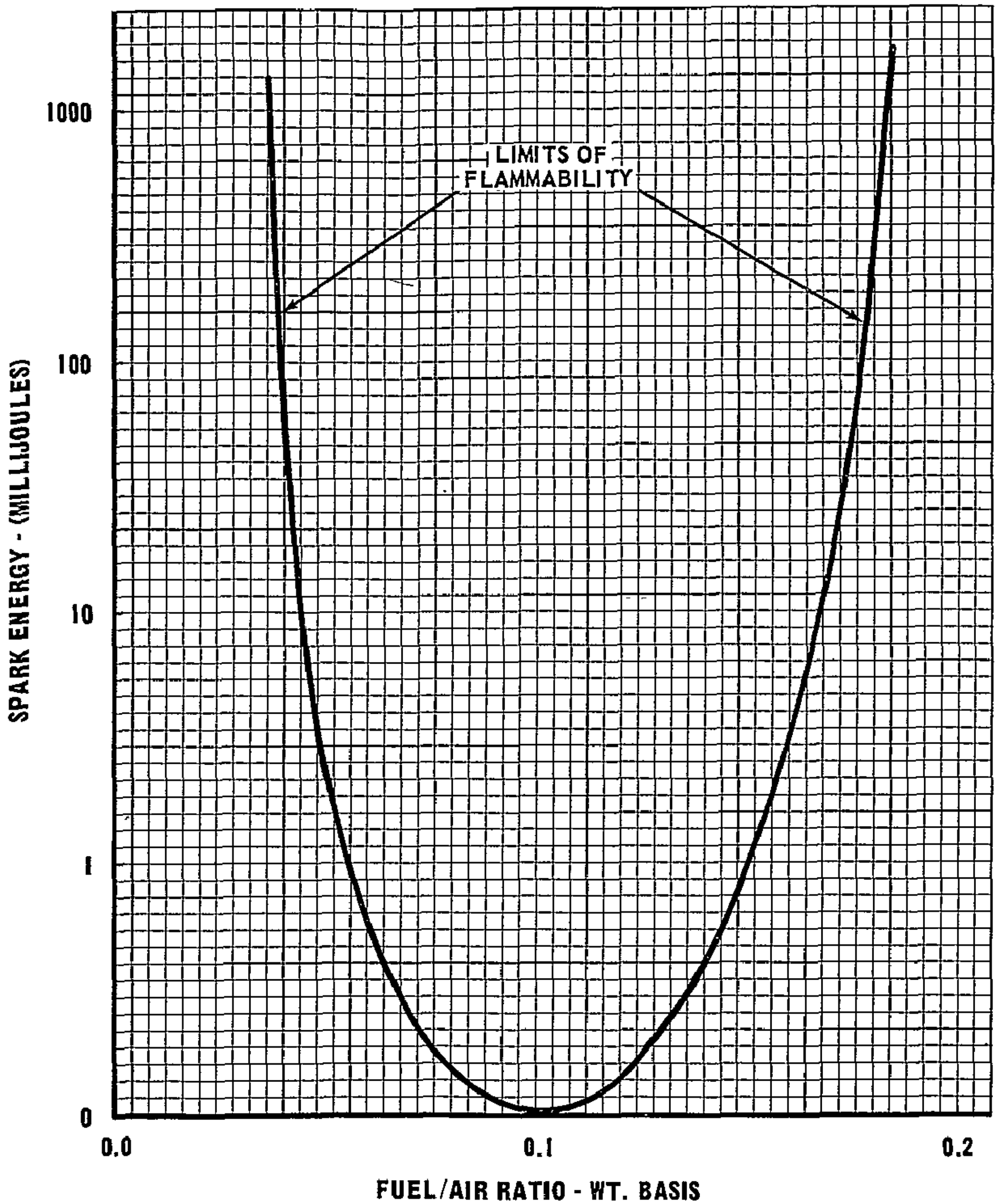


FIGURE 2. MINIMUM IGNITION ENERGY VERSUS FUEL AIR RATIO

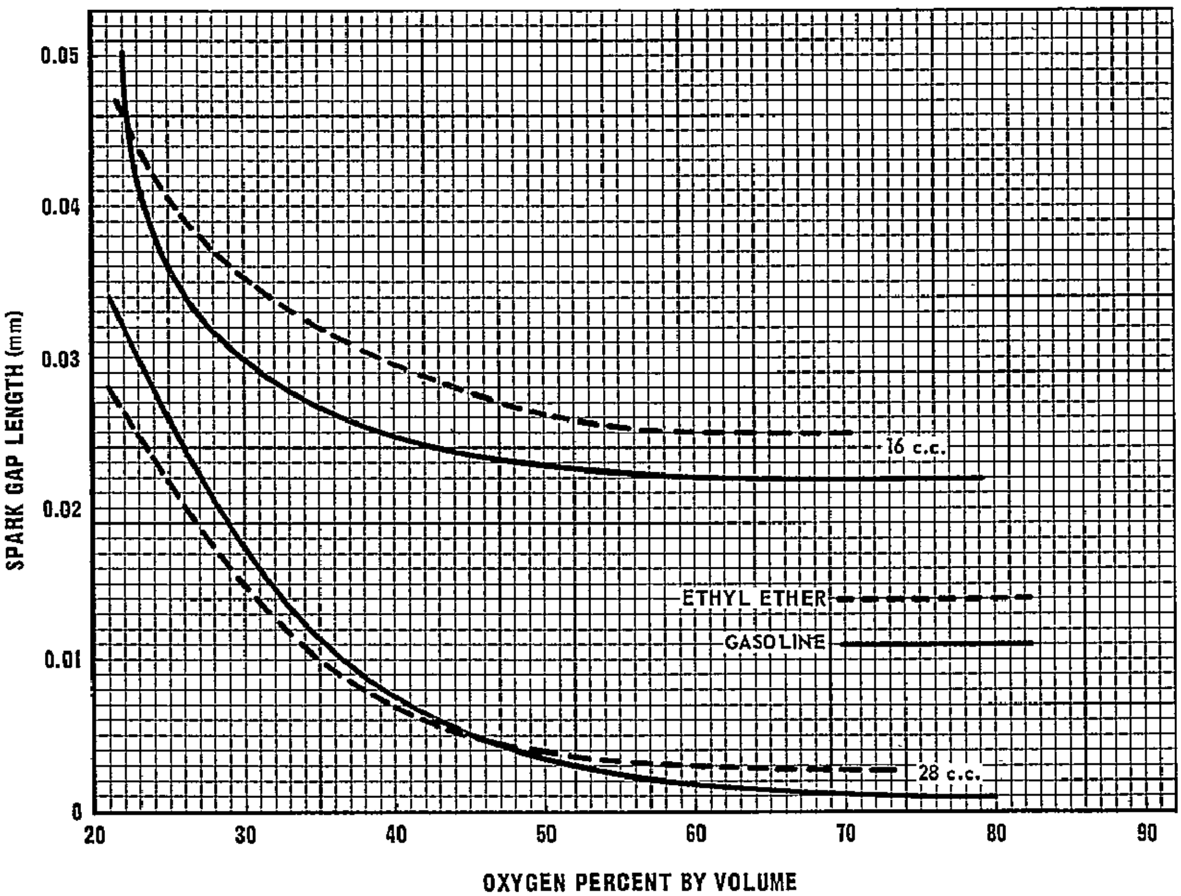


FIGURE 3. MINIMUM IGNITION GAP LENGTH VERSUS OXYGEN CONCENTRATION

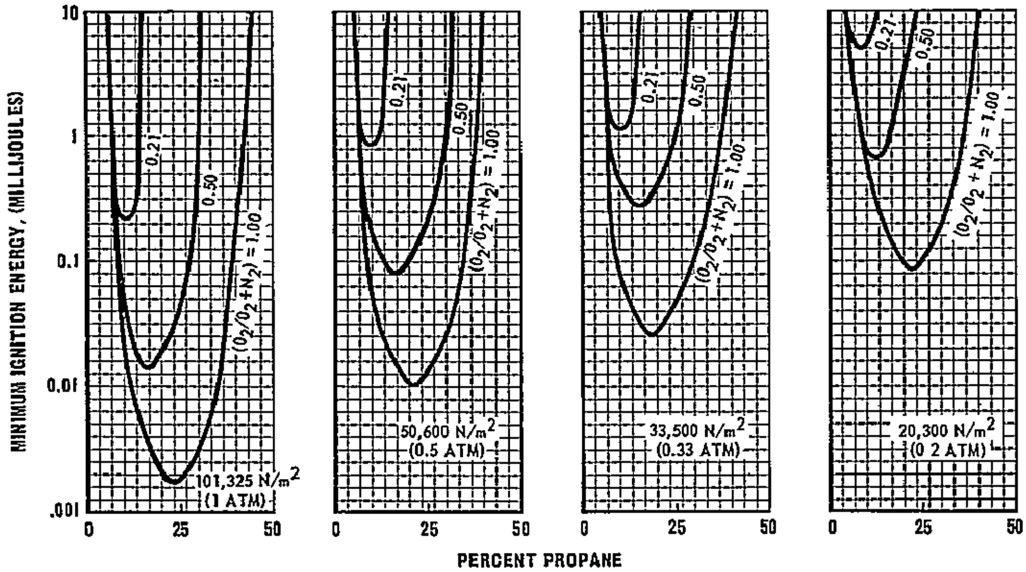


FIGURE 4. MINIMUM SPARK ENERGY AS A FUNCTION OF ATMOSPHERE COMPOSITION

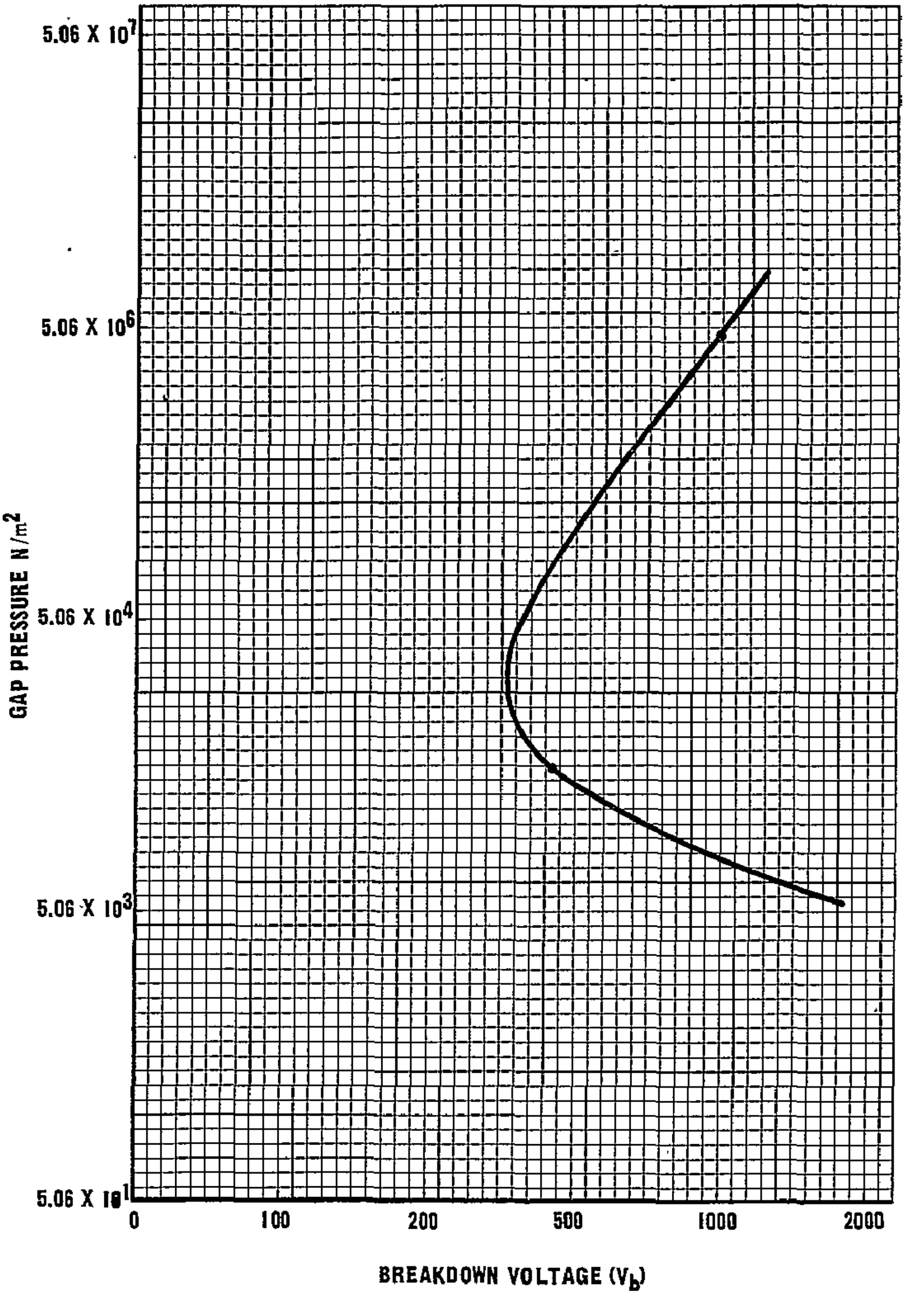


FIGURE 5. ARC BREAKDOWN POTENTIAL AS A FUNCTION OF GAP PRESSURE

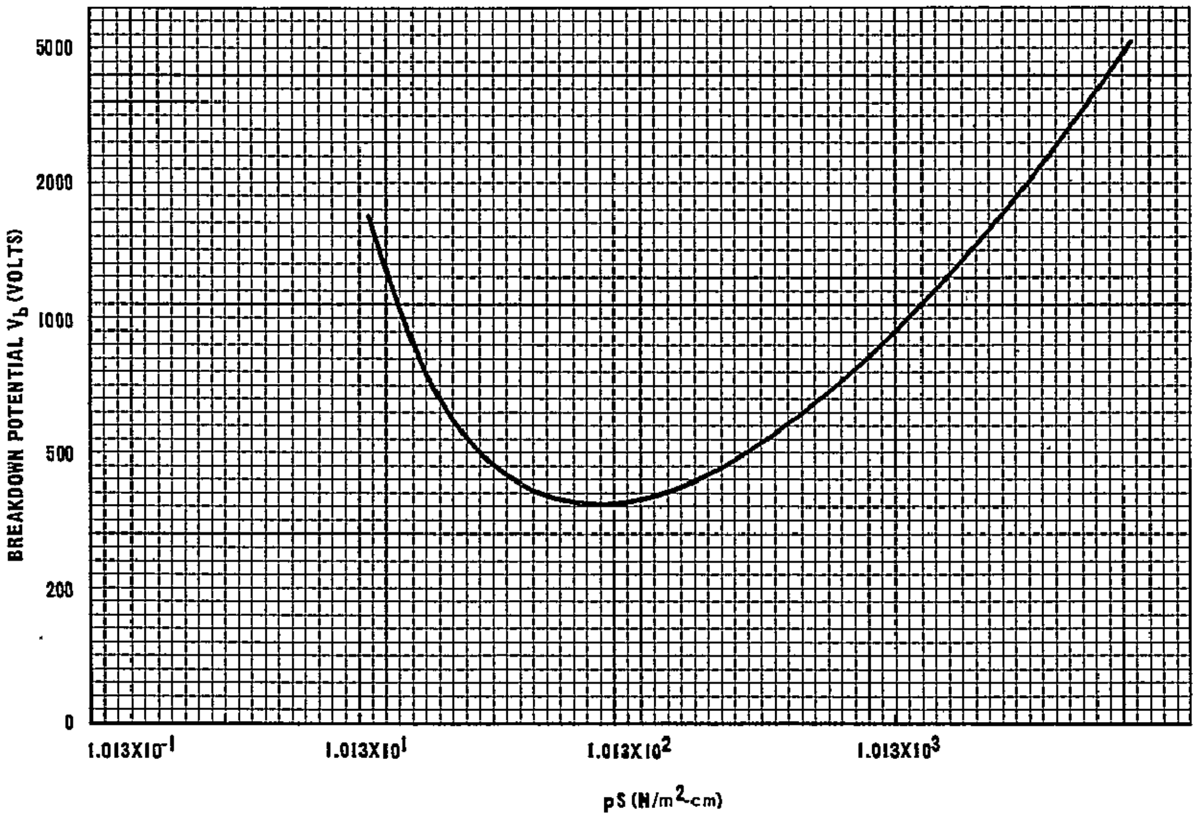


FIGURE 6. BREAKDOWN POTENTIAL AS A FUNCTION OF GAP WIDTH AND PRESSURE

1×10^{-5} cm (1000 Å). He found arc ignition below Paschen's minimum of 330 volts, even down as low as 50 volts. Arc ignition at these very close spacings is explained as resulting from very high field concentrations occurring at surface asperity peaks.

Most electric tools in the range of consideration of this report will use power circuit voltages much lower than Paschen's minimum ignition voltage and even considerably lower than the 50 volts found at extremely close spacings by Germer. The conclusion is that "make" sparks in tools using 30 volts or less do not constitute an ignition hazard from the "make" spark switch source.

An interesting aspect of combining the information from the data obtained from Figures 3, 4, and 6 is presented in Figure 5. Considering a cabin atmosphere of more than 80 percent oxygen content and a minimum gap length in this atmosphere which will ignite most low molecular weight hydrocarbons 0.0025 cm (0.001 in.) we calculate and plot the curve of Paschen's breakdown potential versus gap-pressure. This composite curve shows several important facts relevant to the operation of electrical switches under space cabin and space flight conditions:

1. The electrical breakdown gap length is a minimum in the 100 percent oxygen atmosphere at between 39.99×10^3 N/m^2 absolute (5.8 psia) and 20.68×10^3 N/m^2 absolute (3.0 psia). This pressure range is precisely that range in which past and present spacecraft atmospheres have been operated.

2. Pressures lower or higher than the range 20.68×10^3 to 39.99×10^3 N/m^2 absolute decrease the danger of development and ignition of "make" sparks. The lowest pressure (EVA) is considered a much lower risk. The reduction of "make spark" risk at high pressures suggests that the solution should be a hermetically-sealed pressurized switch.

3. Reducing the electrode voltages below 330 volts, especially below 50 volts, practically eliminates "make" spark risk.

The "break" spark is fundamentally different from the "make" spark. There are two major differences which apply to the conditions just preceding the creation of the "break" phenomenon as compared to the "make" condition:

1. The surfaces are in mechanical contact.

2. Some parts of the surfaces are carrying the circuit current (I_c).

Considerable work has been done on the nature of contact of these surfaces [15, 16, 20]. The actual area of mechanical contact, even for the smoothest surfaces, is at most about 0.1 percent of the apparent mechanical contact area. The electrically conducting area is even smaller and on the order of 0.1 percent of the mechanical contact surface. The conducting spots or constriction areas are thin highly-conductive bridges. The bridges are formed by a process called fritting. "A" fritting generally means the breakdown of insulating films originally found covering the contact surfaces. This breakdown is accompanied by local conduction, intense localized heating of these conducting points, and melting of the fritting spot with subsequent formation of the molten conducting bridges [15]. The actual conducting area is small and the current density in the areas is very high. Contacts carrying only a few amperes, such as a switch cutting the power to an electrically powered hand tool, may have current densities of the order of 10^8 amps/cm^2. The importance of this high current density passing through the resistance is not found in its electrical resistance, which is usually only milli-ohms, but in its thermal capacity. Most of the energy lost in passing through the contact surfaces is lost as heat energy ($I_c^2R_c$) generated in the immediate vicinity of the conducting aspherities. Because of the small thermal capacity the spots exist at higher temperatures. The second stage of the process of fritting, called "B" fritting, operates in such a way as to keep the bridges molten. If the current increases, "B" fritting generally results in the molten spots increasing in size to maintain nearly the same value of constriction resistance and to carry the extra current [15].

Under breaking the contact we start with the molten conducting bridges and begin to reduce the normal load. The area of contact decreases and consequently the constriction resistance, current density, and temperature increase, and the material in the bridge vaporizes as the switch opens. The opening switch thus creates its own high-temperature, highly-conductive, vaporized metal, or plasma path which constitutes the beginning points for the drawn spark or arc. Once such a high-temperature vapor path is formed it will draw out a spark or arc until either the current or voltage goes below a value necessary to maintain the conducting path. These shortest-arc minimum values are known as minimum arc current (I_m) and minimum arc voltage (V_m). Both of these important limits depend on the cathode materials. Values of I_m and V_m for typical switch contact materials are:

	I_m Amps	V_m Amps
Carbon	0.01	15 - 20
Silver	0.45	8 - 12
Copper	0.43	12
Tungsten	1.0	10 - 15

These minimum values are within a range which can be developed in a dc space tool power circuit. The conclusion is that "break" sparks are possible in the low voltage space tool power circuits and constitute a potential ignition hazard.

The extinguishment of the break-spark hazard is possible if we could reduce either the current or voltage before contact separation below the minimums. It should be recognized that in power tool systems a further consideration must be made. These circuits contain inductance and capacitance, and in dc systems undergoing a transient (switching) condition the inductance serves to supply higher transient circuit voltage values than occur during steady electrical conditions. Even though the power circuit could be designed and operated below the minimum arc current (I_m), on switch opening the inductance would operate to prevent any circuit changes, and arc would ignite at:

$$I_o = \frac{E-E_c}{R}$$

where E_c is the last voltage across the switch contacts. After ignition the circuit varies as:

$$E = IR + L \frac{dI}{dt} + V(I,S)$$

where V (I, S), the spark voltage, is a function of I and arc length S.

The presence of capacitance and inductance in most power circuits may lead to arcing and sparking in circuits otherwise operating below I_m and V_m. The inductance may provide voltages higher than the prime supply voltage and pulse currents higher than I_m may be drawn from the capacitance.

Ejecta Particle Sparks. Several types of hot incandescent particles may be created and ejected by tools:

Metal strike sparks. "Sparking" and "non-sparking" metal tools have long been considered in explosive or potentially dangerous atmospheres on Earth. There are two major chances for developing metal strike sparks in space, striking the tool housing and metal sparks generated in the impactor mechanism of some tools.

The U. S. Department of Commerce has done research on the sparking of metals in an atmosphere which has some relevance to space cabin atmospheres. In this work the sparking characteristics and the ignitability of flammable mixtures were tested under increasing concentrations of oxygen. The results of these tests are summarized in Tables I and II. These tests showed that metals safe from strike-sparking, flammable, and explosive high-oxygen atmospheres include maganese bronze, phosphorus bronze, aluminum bronze, commercial brass, aluminum, and beryllium copper. Unsafe metals include carbon steel, carbon-tool steel, stainless steel, and monel (nickel copper).

TABLE I. SPARKING CHARACTERISTICS OF VARIOUS METALS IN A GASOLINE AND OXYGEN-ENRICHED AIR MIXTURE (0.13 M^3 [4.5 ft^3] OF AIR WITH 50 PERCENT OXYGEN)

Rod Specimen		Metal Wheels					
Material	Rockwell Hardness	Carbon Tool Steel Rc 63	H. S. Tool Steel Rc 66	Alloy Steel (Bolt Rock) Rc 56	Stainless Steel Rc 37	Carbon Steel Rc 62	Abrasive Wheel
16 cc Gasoline							
Carbon Tool Steel	B72	X	X	X	X	X	X
H. S. Tool Steel	B92	X	X	X	X	X	X
Stainless Steel	B93	X	X	X	X	X	X
Carbon Steel	B82	X	X	X	X	X	X
Monel (Nickel Copper)	B90	X	X	X	X	X	S(1)
28 cc Gasoline							
Manganese Bronze	B89	N	N	N	N	N	N
Phosphorus Bronze	B60	N	N	N	N	N	N
Aluminum Bronze	B93	N(2)	N	N	N	N(2)	N
Commercial Brass	B72	N	N	N	N	N	N
Aluminum	B56	N	N	N	N	N	N
Beryllium Copper	C22	N(2)	N	N	N	N(2)	N

Key: X - Visible sparks and explosion.
S - Visible sparks no explosion.
N - No visible sparks, no explosion.

Notes. (1) This result is for 28 cc of gasoline.
(2) Second test conducted on a rusted wheel; no visible sparks, no explosion.

TABLE II. SPARKING CHARACTERISTICS OF VARIOUS METALS IN A GASOLINE AND AIR MIXTURE (20 cc Gasoline 0.13 M^3 [4.5 ft^3] OF AIR)

Rod Specimen		Metal Wheels						
Material	Rockwell Hardness	Carbon Tool Steel Rc 63	Carbon Tool Steel Rb 72	H.S. Tool Steel Rc 66	Alloy Steel (Bolt Stock) Rc 56	Stainless Steel Rc 37	Carbon Steel Rc 62	Abrasive Wheel
Carbon Tool Steel	B72	X	S	S	S	S	S	X
H.S. Tool Steel	B92	S	S	S	S	S	S	S
Stainless Steel	B93	X	S	S	X	S	S	X
Carbon Steel	B82	S	S	S	S	S	S	X
Monel (Nickel Copper)	B90	S	S	S	S	S	S	S
Manganese Bronze	B89	N	N	N	N	N	N	N
Phosphorus Bronze	B90	N	N	N	N	N	N	N
Aluminum Bronze	B93	N	N	N	N	N	N	N
Commercial Brass	B72	N	N	N	N	N	N	N
Aluminum	B56	N	N	N	N	N	N	N
Beryllium Copper	C22	N	N	N	N	N	N	N

Symbols: X - Visible sparks and violent explosion.

S - Visible sparks, no explosion.

N - No visible sparks, no explosion.

A fortunate result from these tests is that aluminum and high-aluminum alloys frequently used in the tool housings are non-sparking with respect to strike-. or abrasion-generated metal sparks. Since regular prediction of metal strike-sparks from a tool housing under use by a man is impossible, the only approach that can be accepted is to manufacture the housing of such non-sparking materials.

The condition in the impactor mechanism is more predictable than in the tool housing, is more controllable in design, and can be tested for possible sparking after construction. Most impactor mechanisms have relatively flat anvil/hammer surfaces, with little abrasion and surface shear occurring in use. Simple substitution of non-sparking alloys may be possible since the hardness of non-sparking aluminum-bronze alloys (Rockwell B93) compares favorably with the steel materials (B90 to B92) sometimes used. However, only the tool designer in the original design process can adequately evaluate the substitution of these specified non-sparking alloys in the impactor section. Other factors under the designer's control include maximum impact pressure (the impactor surface area), the shape of the impactor surfaces, and the geometric impacting conditions. Using all the available design conditions the impact mechanism can be made safe from metal strike sparking. Test procedures simulating IVA and EVA use under long term normal and possible failure mode should be used to verify the adequacy of any materials/design compromise, should this become necessary.

Incandescent carbon wear particles. In some space power tool machinery we have situations where carbon elements are in sliding contact with metal surfaces. This occurs in the electric motor where carbon brushes run against metal slip rings or against metal commutator segments. In gas (air) powered tool motors the vanes may be carbon or they may be of phenolic-linen composition which can produce small fragments with high carbon content. The question is whether these particles may become incandescent and serve as a potential ignition hazard.

The literature search shows only two cases translatable to potential space cabin hazards. One case is poor commutation of the electric motor. Poor commutation can be caused by vibration of the brushes, mechanical and electrical defects in the motor, high altitude effects in the brush, etc. Under poor commutation, streamers of hot particles thrown out from under the brush are observed. These are organic impregnations in the brush material which are heated by sparking and arcing during the deficient commutation. A similar mechanism was observed by Buckley [21], whose group investigated sliding carbon wear surfaces on metal both with and without an electrical potential across the carbon-metal interface. Fires in combustible mixtures were generated by incandescent wear particles in these tests, but only when an electrical potential was placed across the carbon-metal interface. For incandescence, the values of voltage and current had to be above 106 Vac and 0.3 ampere. An electric power tool in normal use would carry more than this minimum current, but dc power tools would not be expected to carry this order of voltage magnitude. The hot incandescent ejecta particles observed in electric motors undergoing poor commutation may be caused by momentary surge voltages generated by the motor circuit inductance and capacitance, which can operate during transient high-load electrical conditions and create surge voltages above this minimum. Under this condition the brush may be operating as a special case of the "break" spark found in the ordinary switch.

Electric power tool motors are known to offer the hazard of hot incandescent ejecta particles from the carbon-brush metal interface. The gas powered vane motor is not known to show this source of ignition hazard when operated with compressed air.

Solid state reaction sparks. There are two solid-state chemical reactions which are possible within a space cabin. These solid-state reactions would not be directly dependent on the oxygen atmosphere and would therefore be an equal risk as a spark ignition source within or without the cabin. The two reactions are:

$$Fe_2O_3 + 2Al \rightarrow Al_2O_3 + 2Fe + \Delta H \quad \text{(Exotherm)}$$

$$Ni + Al \rightarrow NiAl + \Delta H \quad \text{(Exotherm)}$$

These two reactions are considered not only because they are thermodynamically capable of producing incandescent particles but also because the solid phases necessary for the reactions may be found throughout the construction of the spacecraft. The iron oxide reaction with aluminum is characteristic of several metals that can be replaced from their oxide lattice crystal formation by the very active aluminum atom. The oxides of manganese, chromium, vanadium, lead, and nickel are also capable of "thermite" reaction with aluminum. Aluminum reacting with iron oxide is the reaction which offers the greatest hazard potential since iron alloys and aluminum are frequent materials of construction within the space cabin and power tools.

The oxide of iron forms normally on most steels and, since the reaction product occupies considerably more volume than the unreacted iron, has little adherence to the underlying base metal, the oxide is usually found scaling off as small particles. The oxides of iron progress from Fe O to $Fe_3 O_4$ and finally to $Fe_2 O_3$, all of which will react. Such small particles, when struck by or against aluminum could become incandescent thermite spark sources. That impact is sufficient to ignite these sparks was quite well pointed our by Kingman et al. [22], working with aluminum paint on rusty steel. These investigators found no difficulty in striking thermite sparks of sufficient incendiveness to ignite combustible gases. All that was found necessary was two reacting components and sufficient impact to start the reaction. Sources of energy such as electric sparks, hot surfaces, friction, and shear would also initiate the reaction in air. The most expected reaction would be between $Fe_3 O_4$ or $Fe_2 O_3$ aluminum. The typical exotherm is:

$$3Fe_3 O_4 + 8Al \rightarrow 4Al_2 O_3 + 9Fe + 793 \frac{\text{kcal}}{\text{kg mole}}$$

Based on this exotherm the reaction can be classed among the high heat fuel reactions and such small incandescent particles would be a definite ignition hazard.

Visible areas of rusty steel such as those with which these researchers worked are not expected inside a space cabin. However, some quantity of oxidation product from the several steels present could be expected and the presence of larger areas of aluminum would also present a situation favorable for the reaction. Such situations might be found where the aluminum housing of the hand tool (gas, electric, or hydraulic powered) might be struck against a steel surface. The ordinary impact metal-sparking characteristics of aluminum against iron are considered to be a "safe" or "non-sparking" combination (discussed elsewhere in this report as metal "strike" sparks); however, slight iron rust would change this.

While oxygen does not enter directly into this reaction, the oxygen atmosphere would be conducive to formation of iron rust; thus the cabin atmosphere is indirectly involved in forming one of the reactants.

Other areas where this reaction might offer danger in tool operation would be inside the air tool rotating mechanism and at the anvil-hammer interface on ordinary impactor mechanisms. The vane-to-housing interface in the air tool usually finds the vanes running a tight fit with high rotational speed against the aluminum tool housing. A particle of Fe_2O_3 would have opportunity to find sufficient aluminum and initiation from impact/shear for thermite reaction. The hammer-anvil impactor mechanisms usually are made of some form of steel. Here an aluminum flake could find both impact and iron oxide particles on the impact surfaces.

The nickel aluminides are formed as a metallurigical solid-state reaction from pure nickel and aluminum [23]. The reaction is highly exothermic and small particles can become incandescent. This material is used as a substrate bond coat in sprayed metal systems; part of its unique ability as such a universal bond coating is that it arrives on the metal surface in such a highly active exotherming condition. When pure aluminum powder particles coated with pure nickel are sprayed through an ordinary flame spray gun the metal particles are observed to be of maximum incandescence beyond the hottest part of the flame. They are found, in fact, to increase their temperature after passing through the flame because of the high exotherm of the Ni-Al solid state reaction. A temperature of 922° K (1200° F) can initiate this exotherm but no information is available indicating the impact sensitivity of the reaction [23, 24].

A complete metallurigical solid solution series is formed between 100 percent aluminum toward 100 percent nickel. This metallurigical formula is usually written:

$$(1-X)\ Al_{(S)} + X\ Ni_{(S)} \rightarrow Al_{(1-X)} + \Delta H$$

where X = Atom fraction of the component
and S indicates reaction in the solid phase
ΔH = Enthalpy change in cal/g-atom

In the Ni-Al series four intermediate phases are known; all combinations are highly exothermic. Any combination above 0.1 mole fraction of either material in the order exceeds 16 736 joule/g-mole (4000 cal/g-mole) in value for ΔH. For most exothermic solid-state pure metal reactions 16 736 to 25 104 joule/g-mole (4000 to 6000 cal/g-mole) is a high exotherm. The formation of nickel aluminides finds a maximum exotherm between 0.4 to 0.6 mole fraction of nickel reacting with aluminum, with the peak exotherm going over 58 576 joule/g-mole (14 000 cal/g-mole).

Aluminum is a common space cabin material, but free nickel is not as common. Nickel is sometimes used to plate aluminum which is to be soldered or have a low temperature braze accomplished later. A spark drawn to such a housing would raise the temperature of the reactants and initiate the self sustaining exotherm. No data on the action of these two materials under impact is available from the literature. Comparing the thermodynamic data of the reaction, the reactants, and the products of the nickel-aluminide to the thermite reaction suggests that Ni-Al would be an impact-sensitive reaction. As such it would operate much as the strike sparks for sparking metals or for impact generated thermite sparks. In the range of approximately equal mole fractions, especially when small flakes of either material were to be brought into intimate contact with the other reactant, an incandescent spark source could result which would be capable of serving as an ignition source.

The pure chemistry and metallurgy of these two different solid-state reaction ignition hazards give only a part of the true picture. The conditions of 100 percent oxygen in the space cabin atmosphere and the EVA use of space power tools bring up additional physical considerations which will now be considered.

Atmospheric constituents do not enter directly into either thermite or Ni-Al reactions. Once initiated, they occur equally well in any atmosphere, in any inert gas, or in the space vacuum (EVA) condition. Their direct reaction hazard does not depend on the presence of freely available oxygen. However, oxygen and the hard vacuum will affect the physical aspects of these reactions. First, the iron oxide reactant which is expected to be the only probable thermite reaction is formed from free atmospheric oxygen. The ignition hazard of this particular thermite reaction depends on the prior atmospheric oxygen history of the iron rust source.

Since these solid-state reactions are hazards as ignition sources the total risk involves the potential for developing a fire in other fuel or combustible materials. The presence of free atmospheric oxygen will determine the potential effectiveness of these hot particles as fire starters. In the space vacuum the risk of fire from ignition by these particles is much lower; perhaps the only risk here is the potential burn-through of the pressure suit.

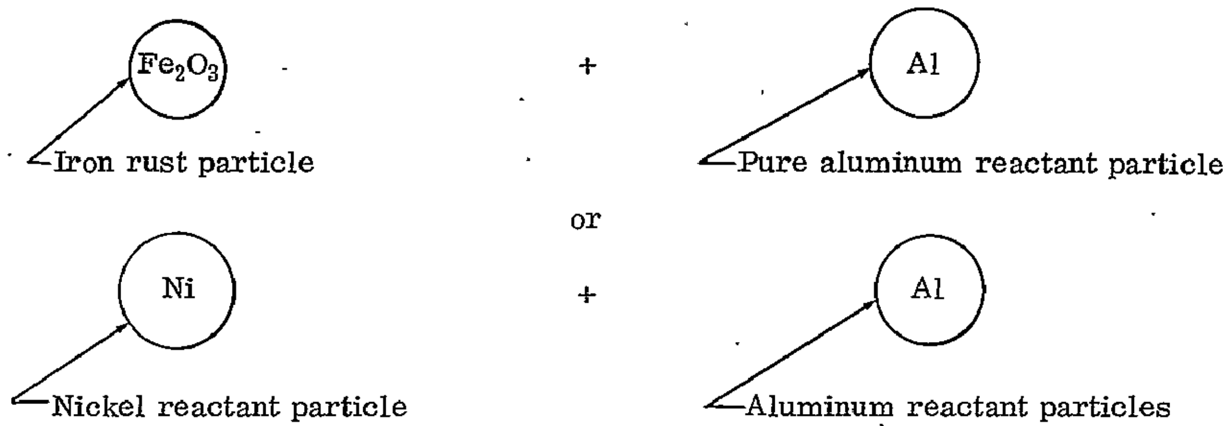
The oxygen exposure history of the aluminum reactant in both reactions will also operate in a very special way to influence the potential hazard. The representation for these reactions is usually written as the chemical reaction:

$$Fe_2O_3 + Al \rightarrow$$

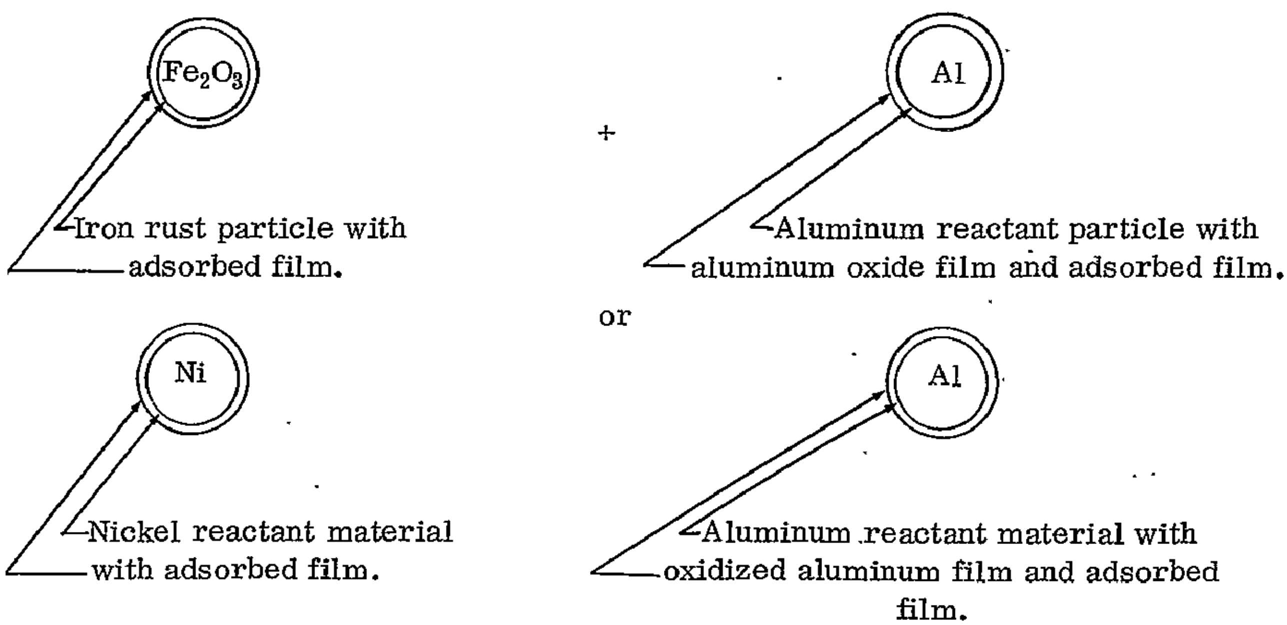
or

$$Ni + Al \rightarrow$$

These type formulae alone imply the physical conditions:



These are not true physical states of these materials under the usual Earth-bound or space cabin atmosphere reacting conditions. A more precise physical picture would be:

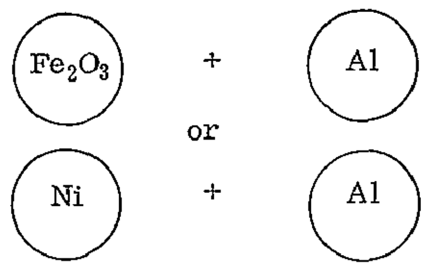


These sketches represent the more correct physical conditions of the atmospheric reactants.

The adsorbed films are only lightly held with forces on the order of Van der Wall's bonding levels. The most tightly held of these would be the polar adsorbants such as water. These films are removed with only small energy levels, can be penetrated rather easily, and do not serve to influence the reaction strongly. They are effectively destroyed by heating to a few hundred degrees. The aluminum oxide film is quite different from these other adsorbed films. The forces bonding the Al_2O_3 within itself and to the base metal are quite high and very stable. The oxide surface is chemically inert and a highly refractory material. It is not broken or penetrated easily and if penetrated will reform almost immediately in the presence of oxygen.

There is no large volume change for aluminum oxidizing to aluminum oxide; therefore, there is no inherent scaling off of the oxide film as occurs during the formation of rust and other oxides. The result of increasing the energy level (heating, etc.) in the presence of atmospheric oxygen is to increase the diffusivity reaction of oxygen through the Al_2O_3 film; and consequently increase the depth of the protective alumina film. In the research by Pilling and Bedworth [25], the actual reaction of metals with oxygen in forming or not forming a protective film is indicated. Metals fall into two categories; the category to which aluminum belongs is among metals which do not ignite until after they melt. Melting and resultant liquid mobility causes rupture in the protective oxide film; effective high-temperature combustion (rapid oxidation) is also suppressed by the adherent alumina film and does not proceed until that film formation process is disrupted. The basic reactivity of pure aluminum metal is much higher than the reactivity found and expected in Earth atmosphere use. This reduction of apparent reactivity and the performance and uses of aluminum on Earth is dependent on the peculiar combination of properties of the aluminum oxide surface, and the normal atmosphere in which we ordinarily use aluminum.

In the space vacuum we may have the physical conditions:



Here pure aluminum surfaces would not form or reform the protective film. Under conditions of hard vacuum the thermite and exothermic metallurgical reactions could proceed with:

1. Lower initiation energies than these same reactions in Earth atmospheres.

2. Higher reaction rates than these same reactions in Earth atmospheres.

Considering that these exotherms are equal to or above the energy levels for many fuel-oxygen combustion reactions they should be investigated as carefully and approached with as much caution as the increased risk of fire in 100 percent oxygen. Under space vacuum, in drilling through aluminum with a steel bit or in cutting or shearing aluminum sheet with high-iron alloy blades, in chiseling, hammering, and other maintenance operations, whether by powered or hand tools, the extra reactivity of non-oxidized aluminum surfaces can offer a greater potential hazard for producing incandescent solid-state reaction sparks than the same operations conducted inside the cabin or in Earth atmosphere.

Hot Surfaces.

Gas and hydraulic power. A survey was made of the minimum plate ignition temperature for various combustible fluids and gases which might be expected within the space cabin. This survey showed that under the maximum oxygen concentration expected in any space cabin the minimum ignition temperature for hot surfaces would be 461 to 478°K (370 to 400°F). From this the maximum safe surface temperature for any exposed tool surface was considered to be 408 to 422°K (275 to 300°F) in this report.

The continuous flow of fluid in both hydraulic and gas powered tools reduces the potential tool housing surface temperature rise well below the ignition temperature during normal operation of the tools. These two types of tools also show safe performance under high-load or stalled-loading conditions. Gas and hydraulic powered tools offer no hazard as potential hot-plate ignition sources under either normal or overload operation.

Electric power. The electric tool has no internal flow of fluid which will carry off heat. The tool generates heat from two major sources, frictional heat in bearings and brushes and electric power resistance heat (I^2R). Heat dissipation is by convection to the atmosphere and by radiation. Space conditions affect frictional heat, developed mainly in the brushes, and both major methods of heat dissipation. The interrelation between these factors is complex; therefore, the several vacuum tests on previous dc electric power tools and the well documented performance of brushes under vacuum were consulted to determine whether the maximum hot-surface temperature of 422°K (300°F) could be expected under vacuum conditions.

USAF report TDR-63-4227 documented the vacuum tests run on a 186-W (0.25 hp) electric impact tool developed by the USAF for space uses. Tool housing temperature was measured at six points on the tool housing and an atmosphere of near vacuum was held 6.7×10^{-3} N/m^2 (5×10^{-5} mm Hg). The test was run for over 2 hours on a duty cycle of 4 seconds on and 3 seconds off. A locking device prohibited the output shaft from rotating, which simulated a maximum load condition. During the two-hour test the thermocouples showed a maximum rise in temperature from around 292°K (65°F) to 353 to 355°K (175 to 180°F).

During this test several problems were noted concerning the operation of the commutator brushes. Increased arcing was observed in all tests. In some tests the brush arcing was considered excessive and the test was halted because of it. Motor brushes were replaced with brushes developed by Stackpole Carbon Co. especially for exposed high-altitude use. These brushes also arced noticeably during the vacuum tests. Although the tests were not halted by test personnel because of visible arcing, the motor did run erratically during tests using these special brushes.

Inspection after the motor stalled showed that the copper brush leads had softened during the test and the brush solder had also melted. Since most solders melt at temperatures above 408 to 422°K (275 to 300°F) and the softening point of copper is also over this temperature, the indication is that these motor brush temperatures were higher than the safe surface temperatures for hot-surface ignition. The brush leads and solder are near the top of the brushes away from the running friction surface. It can be expected that the friction surface, the area on which the friction heat and resistance heat losses are developed, attained a higher temperature than did the soldered end of the brush.

The Martin Company also developed other electric power tools for NASA and for experiments on the Gemini flights [5]. Tool housing temperatures were measured during vacuum tests in both development programs. Operations were usually conducted so that the tool was overloaded beyond its expected use. Case temperatures did not exceed the 344 to 355°K (160 to 180°F) levels and show that the overall motor housing is not normally a hot-surface ignition problem. Problems were encountered in the same area of motor stalling, unexpected low speed operation and excessive electromagnetic radiation (interference). These problems were traced to the motor brushes. No information as to the temperature of the brushes was given in these two tests.

The higher brush temperatures and erratic brush operation experienced in all these tests can be expected. All the available literature on brushes shows that special problems are inherent in brushes operated at high altitude. These special problems have had considerable attention since the early 1940's. Since then regular operation of large numbers of motors on aircraft at high altitudes has been common and the problem and solutions have been studied.

The major basic changes in high-altitude operation of brushes comes with increased arcing resulting from low gas pressure (already discussed in the "switch sparks" section of this report) and the increase in friction of sliding solid lubricants operated at very low pressures. The basic studies have shown that solid lubricants depend on small amounts of certain adsorbed impurities to show the low friction characteristics [15, 20, 28].

Carbon brushes, with the proper solid-state lubricant adjuvants, show normal friction coefficients of 0.1. In high altitude operation, where all water of hydration is driven out of the brushes, the friction coefficients will suddenly increase to values 5 to 10 times normal. The result is catastrophic wear, excessive heat, and generally poor operation of the brushes [29].

The potential (voltage) drop across the brush-collector interface is also subject to small changes in the constriction resistance, which is in large measure a function of the condition of the solid films formed at the interface. Thus, constriction resistance becomes important in determining the electrical temperature generation. In the case of high-altitude operation, the temperature is dependent on only small changes in the constriction resistance. This dependence is shown in Figure 7.

Considering that both friction heat and electrical heat generated at the brush-collector interface are higher and that either heat source may exceed the maximum safe ignition temperature (also considering that convective heat transfer in the vacuum is practically nil), it should be expected that the brush troubles evidenced in the tests are to be incurred under vacuum operation.

Under stalled rotor or other failure mode of operation the tool housing surfaces would become excessively hot, but only after several minutes under stalled conditions. Since the tool will be hand held in use, continued long-time operation at stall can be avoided. The effects of shorted windings and even stall overload can be avoided by fusing the tool. The pressure suit and other protective outer gear and operation within a vacuum will prevent the astronaut from easily sensing a tool housing temperature rise. Therefore some additional device(s) should be built into the tool to indicate tool housing temperature to the astronaut during use.

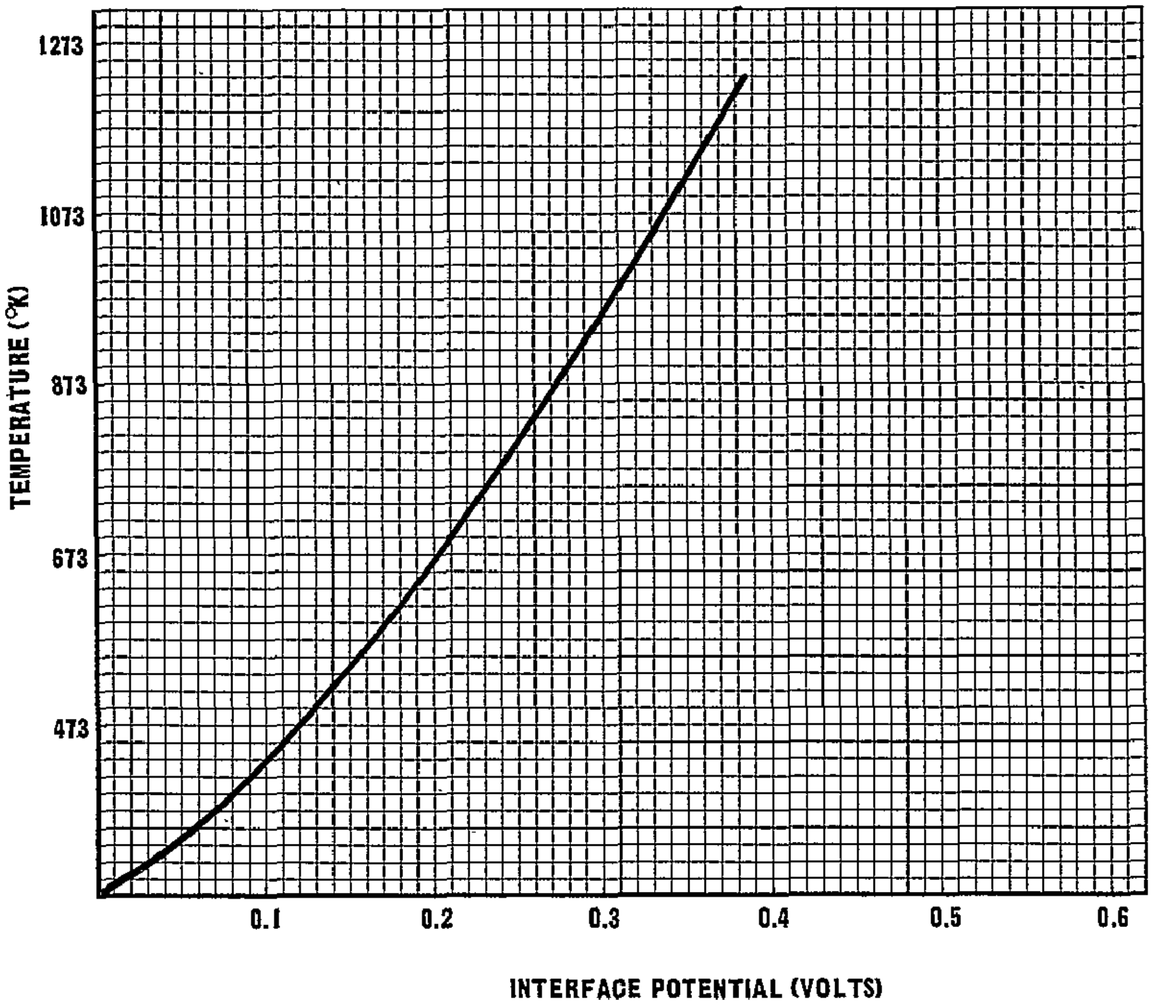


FIGURE 7. CONSTRICTION RESISTANCE AS A FUNCTION OF TEMPERATURE

The Power Tool as a Source of Fuel

Metal Fuels. The major mass of material is composed of the metals of which the tools are manufactured and the metal structures on which the tools are used. Even though metals are not generally classed as fuels, we must be concerned with the fuel potential of metals in combustion reactions. From the standpoint of heats of combustion, metals compare favorably with recognized fuels. Table III shows the heats of combution of several spacecraft materials compared with several fuels.

TABLE III. HEATS OF COMBUSTION

Fuel	Combustion Products	At. or Mol. Wt.	J/kg Fuel	BTU/lb Fuel
Carbon (C)	CO_2, CO	12	32 768 400	14 100
Methane (CH_4)	CO_2, H_2O	16	55 776 000	24 000
Acetylene (C_2H_2)	CO_2, H_2O	26	48 804 000	21 000
Beryllium (Be)	BeO	9	67 396 000	29 000
Magnesium (Mg)	MgO	24	25 564 000	11 000
Aluminum (Al)	Al_2O_3	26	30 212 000	13 000
Titanium (Ti)	Ti_2O_3	47	15 803 200	6800
Iron (Fe)	FeO	56	4 648 000	2000

In determining the relative value of a material as a practical fuel or as a hazard as a fuel, other properties must be considered. The reaction products of the combustion reaction have a large influence on the character of the reaction. Combustion of the common fuels listed above, such as carbon, methane, and acetylene, produce gaseous combustion products which do not interfere with the access of oxygen to the remaining hot fuel surface. Magnesium is a metal fuel which has a solid combustion product (MgO). The cubic oxide crystal particles formed,. however, are not compatible with the hexagonal crystal structure of the basic metal, and evolve from the combustion in a cloud of smoke composed of small white particles. This process is very similar to the combustion of the carbonaceous fuels listed above, and no interference is offered by the MgO product to the further combustion of the parent metal surface. Magnesium is therefore a threat as a metal fuel. This particular reaction is well known and usually is a major consideration in projected aerospace uses of magnesium.

Aluminum's reaction with oxygen has been mentioned previously. The reaction product is tightly adherent to the base metal and serves effectively to block further rapid oxidation at normal temperatures. The temperature of aluminum must be brought well above the melting point of 933°K (1220°F), or to about 1273°K (1832°F), in the highly molten state, before the aluminum oxidation reaction will proceed as a self-supporting oxidation reaction; i.e., before combustion will proceed [30]. While aluminum, from a chemical standpoint, is as reactive as magnesium, and aluminum will supply more heat per pound of oxidized metal, because of the basic nature of its combustion aluminum is not a practical fuel. As a safety hazard, combustion of significant amounts of aluminum will not proceed unless there is another large combustion reaction preceding the high-temperature combustion of molten aluminum. Therefore aluminum is not a practical safety hazard.

Titanium is similar to aluminum. Although the oxide reaction product is not as adherent, it will tend to protect the metal. Research on titanium combustion in 100 percent oxygen showed that titanium would ignite spontaneously under static conditions in pure oxygen and at pressures of 24.13×10^5 N/m^2 (350 psi) or more, but only if a fresh surface is created, such as by scraping the surface. Under dynamic conditions, such as material rupture under stress, the same condition applies, but down to pressures as low as 34.47×10^4 N/m^2 absolute (50 psia).

The practical value of any metal fuel, then, is complex and will depend on the heat of reaction; rate of reaction; ignition temperature; stability, physical, and chemical nature of the reaction products; dissociation pressure and heat capacity of the reaction products; and the specific conditions under which the fuel and oxygen are supplied. For solid metal fuels, no special differences in their combustibilities can be found in space flight except for the potential for a much higher reaction rate in 100 percent oxygen. Safety considerations as are usual in aerospace work should be sufficient in selecting metal materials for power tools.

Powdered metals offer a very different degree of hazard as a fuel supply than do solid metal fuels. Powdered metals dispersed in air form explosive mixtures with ignition temperatures much lower than those of the corresponding bulk metals [30]. Since a relatively high ignition temperature is the one common characteristic which puts most solid metals out of the class of a practical fuel hazard, the drastic lowering of ignition temperatures in the finely divided metal powders brings powdered metals definitely into the high-hazard category. Higher reaction rates when exposed in 100 percent oxygen atmospheres will add to this hazard. In addition, under zero or subgravity conditions the larger particles of metal will tend to "float" and remain a part of the dispersed metal powder, with no natural falldown of such particles. Therefore, any process which produces small metal particles will be accumulative toward a hazardous situation. Production of metal chips and metal powder by tool operations, unless completely controlled, will bring about a definite safety hazard. Such operations will produce a dispersed metal fuel with inherent high heat release and inherent high rates of reaction, a fuel which can be ignited by common ignition sources. Such dispersed metal fuels should be considered as a hazard equal to highly combustible gaseous mixtures.

The Electric Power Tool as a Source of Fuel. Provided the power tool is manufactured of metals ordinarily reasonably safe as fuels under 100 percent oxygen (i.e., not made of magnesium), then the only potential fuel supply from an electric tool will be contained in the content of the lubricants and the wiring insulation.

The amount of lubrication required in an electric power tool is small and under normal circumstances solid lubricants are used. Polytetron fluorethylene (PTFE) and Teflon represent almost completely nonflammable lubricating materials. These materials are ignition-safe even in 100 percent oxygen. Dry molybdenum disulfide will not burn in air, but incandesces slowly in oxygen. Under these conditions the binders are expected to be the fuel contributor and may be controlled by specification to the MoS supplied. Tri-cresyl phosphate is accepted by the Canadian Fire Research Organization as the lubricant for work in oxygen, even though it will burn slowly under 100 percent oxygen. The quantity required in small electrical power tools is so small that this lubricant does not present a fuel hazard.

There are several military standard and commercial standard types of wiring insulation which are accepted as nonburning or generally considered noncombustible. Some of these materials will burn in 100 percent oxygen. Those that will burn include polyvinyl chloride, glass fiber and asbestos. PVC is typically one of the class of safe materials in air but unsafe in 100 percent oxygen. The glass fiber and asbestos materials are not inherently unsafe; they will burn only to the extent that they contain certain binders added in their manufacture which will burn in 100 percent oxygen but will not burn in air. Teflon and PTFE appear as good noncombustible electrical insulators along with specially made glass or asbestos materials.

The mass of fuels represented by the electrical insulation is large enough so that it does offer a threat as a fuel. Insulation must be carefully selected and tested under 100 percent oxygen conditions so that this threat is removed from the tool in its original design stage.

The Gas Power Tool as a Fuel Source. Provided the gas power tool is manufactured of metals ordinarily reasonably safe as a fuel when used under 100 percent oxygen (i. e., not manufactured of magnesium), then the only potential fuel supply from the gas tool will be contained in the lubrication required.

The requirement for lubrication in the air tool is critical to its operation and is a continuous "flow through" type requirement. The last item in the air line feeding the air supply to the tool will be the lubricant reservoir and injector. Additionally, the tool may have its own internal lubrication reservoir. Most of these systems operate with the amount being supplied giving an "oil-wet" exhaust condition, when being properly lubricated. This excess oil is carried off with the exhaust air and diluted into the terrestrial shop atmosphere.

Lubrication in the gas tool performs several vital functions other than reducing friction and wear [6, 31, 32]. The liquid lubrication medium is used as a thinline liquid pressure seal running at the vane-housing interface. It also assists in removing heat directly from the sliding vane-metal housing friction surfaces, and it flushes out particles in the motor.

Oil is vitally necessary for developing power in the air tool. This is illustrated by following the progressive deterioration sequence of an air motor running without lubrication:

1. First, there is a drop in speed and power immediately upon losing the pressure sealing function in the motor.

2. The cylinder liner heats as a result of increased blade friction and the resulting charring of the vane-blade.

3. An additional power drop which is caused by the char and dirt, which is no longer flushed out.

4. There is scoring and excessive wear by accelerated abrasion.

5. Further damage is done by worn blades riding at an angle and gouging the housing liner or by blades breaking and chipping off.

The minimum amount of oil usage appears to be two drops per minute 0.0024 m^3/s (25 cfm) being used. Approximately 0.00316 $m^3/s/W$ (50 cfm per horsepower) is required in the small fractional size motors. For a motor with 186 watts (0.25 horsepower), about 0.0057 m^3/s (12 cfm) will be used near load speed, or an oil usage of one drop per minute per tool. If only a small percentage of this amount of ordinary lubricating oil accumulates in some part of the tool, it will represent a very hazardous fire situation. At some point the oil must be exposed to the 100 percent IVA environment, unless the gas exhaust system is completely sealed and vented overboard. Such an oil vapor in 100 percent oxygen is one of the most volatile fuel-oxidizer mixes available.

The gas power tool offers a fuel supply hazard that is inherent in the relatively large amount of "flow through" lubrication. The safety hazard is offered as pooled oil within the tool or as a vaporized fuel-oxidizer mix within the cabin.

The Hydraulic Power Tool as a Fuel Source. The hydraulic power tool will have whatever fuel hazard is offered by the type of prime power used, whether electric or gas drive. In addition, it will have its own special potential contribution to the fuel hazard.

The major contribution to a combustible fuel supply in all the types of power tools considered would easily come from the hydraulic power source. The amount of fluid circulating would cause a major problem if damage to the tool occurred. Ordinary leaks that are standard in such equipment would be excessive within a closed ecological system. The condition of being able to collect easily at a single point and to vent this effluent from ordinary leaks would not be as readily accomplished in the hydraulic system as it was for the pneumatic.

Research has shown that the conditions in space cabins greatly increase the danger of conflagration should hydraulic fluid be let into the cabin. From this research, Figure 8 shows that all hydraulic fluids decrease in spontaneous ignition temperature (S.I.T.) when the atmospheric oxygen content increases. This decrease is from S.I.T. of 644 to 672°K (700 to 750°F) for most high-temperature hydraulic fluids at normal oxygen concentrations to 519 to 533°K (475 to 500°F) at high (space cabin) oxygen concentrations. These so-called high-temperature fluids ignite at about the same temperature as the standard fluids under the high-oxygen condition.

The combination of high probability and the consequences of a hydraulic system fuel fire was considered to be too great to allow the use of hydraulics within the space cabin [2]. Another USAF study (as yet incomplete) recommended that only solid, brazed, pressure-tested hydraulic joints be considered, and that no flexible hydraulic lines be allowed inside the manned compartment.

The conclusion is that probably the most serious fire hazard is offered by the hydraulic power source. From a safety standpoint, this source is probably too dangerous for consideration.

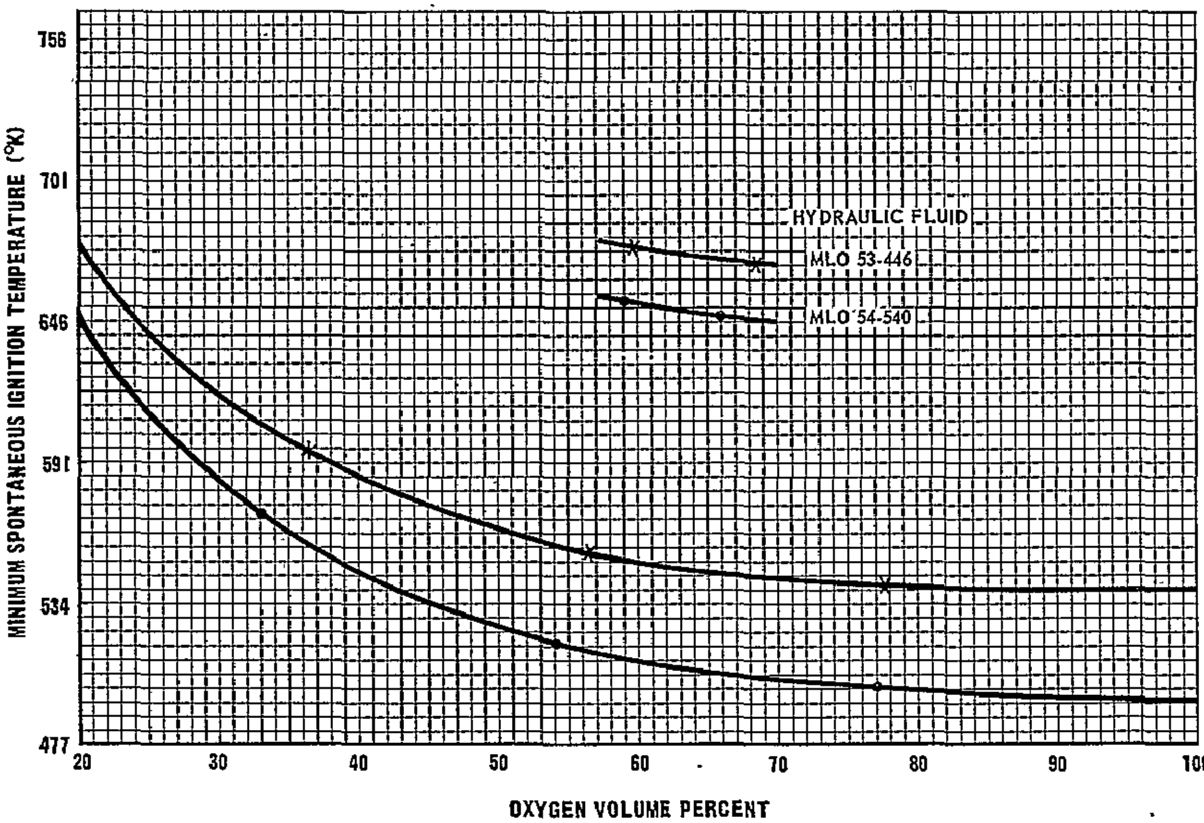


FIGURE 8. MINIMUM IGNITION TEMPERATURE AS A FUNCTION OF OXYGEN CONCENTRATION

TOXICOLOGICAL HAZARD

The Electric Power Tool as a Toxic Producer

The electric power tool has two conditions under which it will produce potentially toxic substances, ozone produced at the brush-commutator interface, and pyrolysis products from overload failure or electrical fire in the tool.

The production of ozone from oxygen fed through an electrical arc is a well-known phenomenon. The increased susceptibility toward arcing and sparking at the brush-commutator interface at low atmospheric pressures is also well documented. These two facts would support the potential for the brushes in an ordinary electric motor to produce ozone during use.

The Martin Company, in developing the electric-drive Multipurpose Space Tool for both the NASA and USAF programs, tested their tools for ozone production. These tests as described were not complete enough to give assurance that all such electric tools, or even those tested, were sufficiently free of production of harmful amounts of ozone. This remains a little-defined problem which must be fully proven by test before any open-brush motor is declared sufficiently free of ozone production to be safe from this hazard.

The pyrolysis products from many electrical wiring insulations are more dangerous than the small fires which produced them. While the fire may be small, the contribution within a small-volume closed ecological system by pyrolysis of the windings of only one motor would add to, approach, or exceed the threshold limit values set for these products. Most toxicological threshold limit values are based on 8-hour exposure for a working week. Toxicologists agree that these values must be drastically reduced within the space cabin. Here the occupants are under essentially a foreign atmosphere (100 percent oxygen), exposed continuously, and the accumulative effects of many toxicants never before placed simultaneously must be considered. In addition, the environmental control systems have only limited capacity to remove solids and certain gases, and may be overloaded with only small amounts of unexpected toxicants.

Part 1 of the Space Cabin Atmospheres study is devoted entirely to oxygen toxicity. Under the exposure conditions of spaceflight, especially long duration 100 percent oxygen, even oxygen becomes suspect as a toxic gas. The additive effects of toxicants plus the relatively small real time experience for humans under such conditions requires the reduction to zero or near zero for foreign toxic materials.

The electric tool may produce ozone at the brush-commutator interface in amounts which can be dangerous and under fire-failure mode the pyrolysis of electrical insulations may be a greater hazard than the fire itself.

The Gas Powered Tool as a Toxic Producer

The lubrication added to the tool appears as a toxic irritant even in small amounts, and in accumulated running of a single tool over one hour (in the Apollo volume) will represent a systemic toxic level.

The gas power tool produces a toxic condition inherent in its present design and operation.

The Hydraulic Power Tool as a Toxic Producer

The hydraulic power tool will have the hazard inherent in the type of prime power driver. In addition, it will have the added hydraulic fluid from small leaks. For present hydraulic systems this would amount to a quantity added of approximately one-fourth that produced by the gas power source.

SPECIAL TOOL HAZARDS

In addition to the hazards listed above, these power sources offer certain special hazards.

The electric tool may offer the electric shock hazard. The past electric tools, which were operated under 15 volts, do not offer a practical electrical shock hazard. Deciding precisely at what voltage we get into this type potential hazard may be difficult, but if operated under 30 volts, it seems that no practical hazard exists.

The hydraulic tool offers a special hazard. The hydraulic fluid is operated at high pressures; if such a high-pressure line is broken, the high pressure spray of hydraulic fluid near the break is found to have a much lowered spontaneous ignition temperature. This effect is very similar to diesel injection ignition. This increased risk adds to the large fire hazard already discussed concerning this type power tool.

SUMMARY AND CONCLUSIONS

This study has shown that hydraulic, electric, and gas power sources offer safety hazards when used as space power tools.

The hydraulic power system must be driven by either an electric or gas power source and will therefore have the inherent disadvantages of the chosen prime power source. The hydraulic system offers a major fire hazard, especially should a failure occur in the hydraulic supply system. Because of this hazard it is recommended that hydraulic systems not be considered where there is any IVA requirements.

The gas power tool offers several hazards. Any tool housing manufactured of high-aluminum alloys will have a natural insulating, auto-oxidized surface or may have any extra thick anodized surface of aluminum oxide. Even if the aluminum is electrically grounded this surface film will be potentially effective in allowing an electrostatic spark to build up.

There are two solid-state reactions which can occur to create incandescent hot particles. Both reactions involve aluminum metal. One reaction is aluminum with iron oxide (rust); in the other aluminum is reacting with nickel. Both will operate in either the presence (IVA) or absence (EVA) of gaseous oxygen. Both reactions may be initiated at lower temperatures and may react at faster rates in space because of the lack of free oxygen to form a protective film. Any drilling, cutting, or shearing of an aluminum/steel combination will involve this potential reaction.

These solid state reactions are not a hazard peculiar to the air tool but may occur with any tool system where the two reactants are brought into intimate contact.

The major disadvantage peculiar to the gas tool is found because of its high, continuous liquid lubrication requirement. This lubrication represents a fire hazard if accumulated into a small "pool" condition and offers a major hazard as a vaporized fuel expended into the 100 percent oxygen cockpit environment.

Dispersed lubrication accumulating within the environmental control system is also a toxicological hazard.

There are also several hazards peculiar to the electric power tool. Unless the electrical wiring is chosen for its heat-failure mode under 100 percent oxygen conditions the wiring may offer both a small fuel supply hazard and a larger hazard in its emission of toxic pyrolysis products. The metal case may strike sparks unless "safe" metals are used in its manufacture. The on-off switch may serve as a spark ignition source, especially on the break-circuit condition.

Several hazards occur as a result of the requirement for carbon brushes carrying current through slip rings and commutators. The brushes may create the toxicant ozone; brush arcing and sparking will create radio magnetic interference (RMI or EMI). This arcing may also serve as an ignition source for gaseous combustibles or severely arcing brushes may eject incandescent carbon particles. The hot brush surfaces may also serve as ignition sources. Brushes running in vacuum will be generally unreliable and have high or catastrophic wear [28].

Both the electric and gas power tools offer some hazard when used in space flight. Some research and development must be accomplished if these tools are to be considered as a completely safe power source.

This study has shown several hazards peculiar to tools, and also several that are important hazards not specifically limited to power tools. These hazards will be listed again since they may apply in many aspects of space flight.

1. Production of free metal powder and chips in an IVA environment, especially if the environment is 100 percent oxygen, produces a highly combustible mixture that can be ignited well below the bulk ignition temperature of the metal.

2. There are two dangerous heat-envolving solid-state reactions of aluminum with iron oxide (rust) or nickel metal. These reactions may be initiated at lower energies and have faster, more energetic reaction rates in the hard space vacuum.

3. Grounded aluminum structures may present an electrostatic spark hazard because of the ever present alumina or insulating film on the aluminum surface.

RECOMMENDATIONS

Neither the electric nor the gas power tool is sufficiently safe. In deciding which one of them will be improved there are three major considerations:

1. The development program must resolve the major safety hazards without sacrifice of tool performance or tradeoffs that will introduce other hazards.

2. There should be high confidence in the end result of the development program before it is undertaken.

3. There should be no other outstanding deficiencies in the power source chosen for development which would effectively prohibit its real value for use on active missions.

This study has been conducted within the considerations of safety and reliability. From a safety standpoint all the inherently extra hazardous high-energy fuel cycles have been eliminated. A previous study showed that even using maximum-energy cycles the gas power source was at a disadvantage when compared on a power versus fuel weight basis. With safety considerations limiting gas tools to only low energy pressure-work systems this disadvantage is increased. From the standpoint of weight requirement there is a practical question of whether such a power source could be accepted.

Positive predictions of the improvement of the gas tool for use in space flight are also difficult. Where we have extensive statistical background of use of electric motors in many protected and exposed locations on high altitude aircraft we have no equivalent background on air motors other than terrestrial shop use. Where the difficulties with the electric motor have been extensively researched and basically well defined both practically and theoretically, the development program for the gas power tool would have neither large amounts of practical information nor be based on deep theoretical knowledge about the processes involved.

Suggestions to make use of some special advantage of the gas tool in order to increase its positive value are also difficult. It has been suggested that such a tool use oxygen as the gas, and to supply the vented gas to the cabin atmosphere as the human oxygen supply. The human oxygen requirement is much lower than the tool gas use requirement. On Gemini flights only 47.17 kg (104 lbs) of oxygen was carried including reserves for 2 men for 14 days [33]. The long-term average use is expected to be 0.9 kg (2 lb) of oxygen consumed per day for each man. Figure 9 shows typical performance curves of a gas power tool of hand tool size (approximately 186 W or 0.25 hp). The flow-rate requirements show that with a 50 percent on-off duty cycle only a few minutes of tool use would produce enough oxygen to satisfy the daily requirements of the astronaut. A more economical gas use may be effected through a development program but it is doubtful whether a gas power source can be brought into energy balance with the gas useage requirements of the human body. Any such scheme of use of the gas effluent from the tool inside the cabin brings the tool directly into the environmental control system loop and will generate additional problems.

The electric power source offers a favorable contrast for possible improvement. Should the major safety hazards be eliminated the electric tool has other very favorable characteristics for use in space flight.

Two development options offer some confidence in being able to make the necessary improvements in the electric power tool.

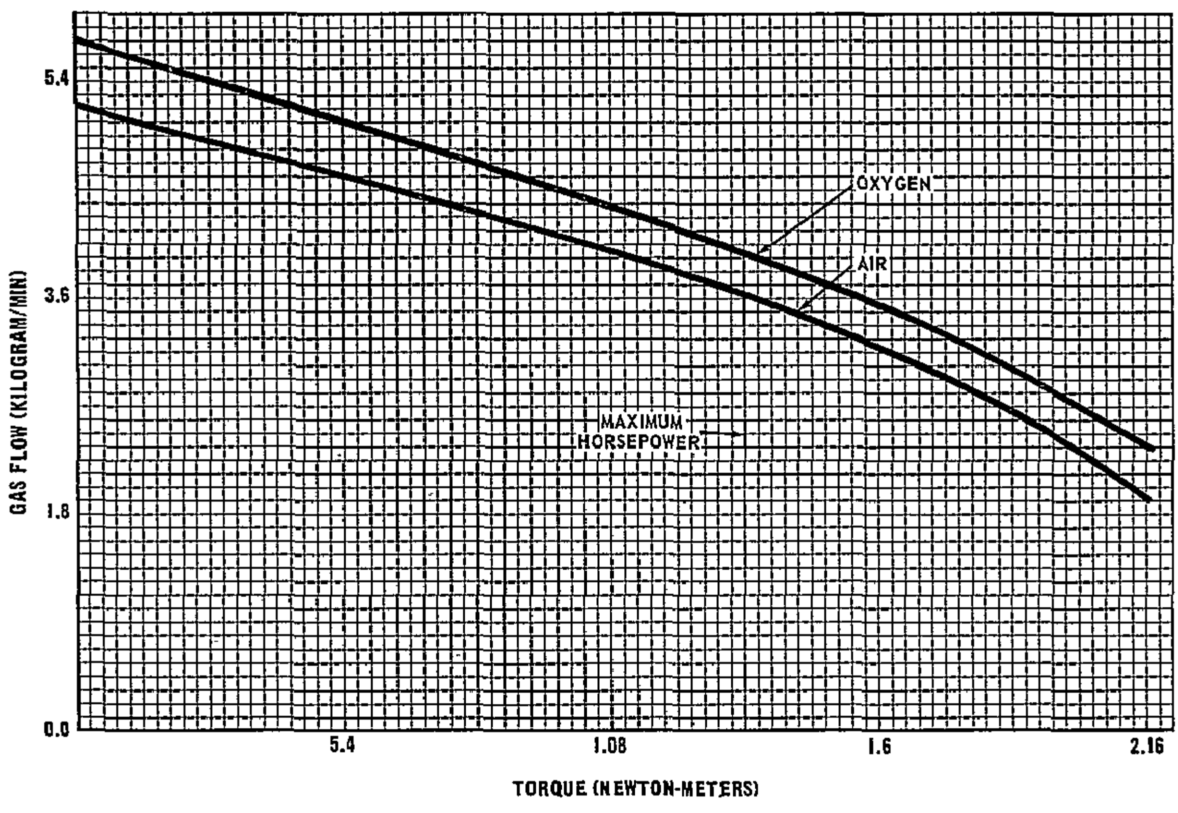


FIGURE 9. TORQUE PRODUCED BY FLOW OR VARIOUS TOOL GASES

One method would be to adapt the higher frequency ac induction motors, for space tool power source. Such a motor would operate on 300 Hz or higher ac power. Its advantages are known in ordinary shop use to be sufficient to shift some shops to this type tool in spite of the requirement for a frequency changer [34, 35]. It would remove most of the problems associated with a brush-commutated dc motor but would introduce the problem of obtaining and using a type of electric power not developed by the prime space-electrical systems. It would require a frequency changer and would also introduce the electrical shock hazard.

The other electrical development option would be to adapt a new type of brushless dc motor, previously developed by NASA for satellite and space power applications, to a configuration and size for use as a power tool drive.

This development was previously accomplished by NASA and the Sperry Farragut Company [36, 37]. The objective on the original program was to develop a very small low-wattage motor for special use in hard vacuum space conditions. It is a true dc motor and its unique properties and design are based on a photosensing solid-state commutator system. In this design the rotor is a permanent magnet while the stator contains the windings. A small light shield is attached to the rotor which rotates around a stationary lamp. The lamp is operated under derated conditions and a light beam passes out through the light shield. Photodiodes in the stationary commutator section sense the position of the rotor. Signals from the photodiodes control a solid-state amplification and power switching system which energizes the proper stationary armature coils. The input dc power is thus switched and commutated without transfer through a brush or sliding contact and without transferring to a rotating electrical component.

This system will eliminate the brush problems of arcing and sparking, the potential to produce ozone, the hot-brush surface ignition hazard, high friction and wear, and general low reliability of the brush commutator system.

Because of the unique design, other safety improvements can also be accomplished. Since the stationary armature windings do not rotate it is practical to consider encasing these windings and pressurizing the case with an atmosphere safer than 100 percent oxygen. Such a hermetically sealed motor would have a much lower fire hazard from the electrical insulation but in case of fire could be built to contain the pyrolysis products. Thus even under failure-mode operation the motor would fail-safe with respect to its potential toxic (fire) hazard.

Solid-state devices are used throughout the main power circuit. This allows the consideration in the design to use a low-power solid-state "gate" switching sub-circuit at the on-off motor switch. If accomplished, solid-state switching would allow the motor to be controlled by a power circuit where the order of magnitude for voltage and current would be 0.5 to 0.75 V and 200 to 300 mA. Accomplishing these low switching values and isolating this switching circuit from the main power circuit may allow the switch to be maintained at all times below both the critical minimum voltage and minimum current necessary to produce the "break" switch spark. This would completely eliminate the switch as an ignition source.

This motor to date has seen several specialized applications since the first low wattage (fractional horsepower) model was developed. There have been at least four different sizes designed for several different uses on satellite systems. Although no design suitable for use as a tool power drive has been produced, the original concept has been scaled up to a 746 W (1 hp) motor pump drive.

There should be no major limiting reason why this type motor cannot be produced in a size, power, and torque range suitable as a power tool drive. Since the solid-state commutator will be heavier and will occupy more volume than the brush commutator, design attention should be given to the possibility that some of the commutator system be placed at the source of power; i.e., in the tool battery housing for a portable system, or at the power plug in a ship-supplied system.

The photodiodes and the power diodes produce some heat and this must be conducted away since these devices do not operate properly at temperatures above 366° K (200° F). Keeping these solid state devices cool may be the only design difficulty, but it should not be a limiting design condition.

Several other features should be included in the motor development and design. The motor should have a simple system to indicate housing and internal temperatures. This may be a self-powered circuit (thermocouples) with a gauge indicator built into the rear of the case, or temperature indicating paints may be used. Several temperatures points should be measured so that localized heating would be registered.

The power circuit should be protected with a fusing system so that sustained electrical overload would not be possible.

Collateral with safety improvements in the motor it is recommended that studies be undertaken to:

1. Investigate the ability of the insulating alumina film, formed on grounded aluminum, to store an electrostatic charge. Auto-oxidized and various anodized aluminum alloys, including the heavy hard coat process, should be investigated. Should the practical hazard from such electrostatic sparks be proven through this investigation, then conducting coating of nonauto-oxidizing metal should be developed. This thin coating would modify the surface of the aluminum so that effective insulating films would not form and the surface could be electrostatically grounded. Such a coating would not appreciably alter the favorable properties of weight, strength, and safe strike-spark characteristics of the basic aluminum. It is suggested that the coating could be a 2 percent beryllium copper coating applied by flame spray or vacuum metalizing. In developing the coating a process must be used which will place it onto the conductive aluminum surface and effectively ground potential capacitative spark development.

2. Investigate the solid-state reactions of iron rust with aluminum and nickel metal with aluminum while under the conditions of hard space vacuum. Quantitative values can be placed on the temperature of initiation and the rate of reaction by a research method such as differential thermal analysis while under vacuum conditions. Whatever method of analysis is used it should be based on providing an atomically clean unoxidized aluminum reacting surface. It should provide practical and quantitative theoretical answers to the development of incandescent sparks when performing drilling, cutting, and other operations in space on aluminum with rusted steel tool surfaces.

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APPROVAL

SPACE TOOL POWER SOURCE SAFETY AND RELIABILITY INVESTIGATION

By

Manufacturing Research and Technology Division

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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