RADIATION EFFECTS ON AIRCRAFT TURBINE LUBRICANTS

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ABSTRACT

Samples of three aircraft turbine engine lubricants, MIL-L-7808, MIL-L-9236, and GTO-790 (complex ester), were irradiated in a Dynamic Test Loop at Convair-Fort Worth. Each oil was exposed to the GTR flux for approximately twenty hours. A common dose-rate of 4.1×10^8 ergs/g(C)-hr and 8.1×10^9 n/cm^2-sec (energies above 2.9 Mev) was maintained. Test samples were withdrawn about every two hours during irradiation and oil properties measured. The data are presented and comparisons made of the radiation resistance of the three oils. A brief summary of radiation effects work at other facilities is included and comments on the need for future work are made.

INTRODUCTION

The use of controlled nuclear fission as a primary power source for aircraft propulsion will soon be a reality. Aircraft performance characteristics will benefit substantially from the increased power per unit-weight of fuel. Due to security restrictions, no details of nuclear aircraft configurations or propulsion systems are discussed in this paper. It is general knowledge, however, that several models are under consideration.

Inherently associated with the fission process is the emission of neutron and gamma radiation. This radiation constitutes an additional environment in which the systems of the nuclear-powered aircraft must operate. Consideration must be given to the effects of this environment on the performance and lifetime of aircraft component parts.

One area of acute sensitivity to nuclear radiation is organic fluids. Organic lubricants, hydraulic-power media, flotation and damping media for navigation instruments, auxiliary power fuels, and other fluids will probably be in service aboard the aircraft. Each fluid will have certain properties that are critical by virtue of its particular function. These properties must be maintained within desirable limits in the nuclear and nonnuclear environments of the system. The Air Force has sponsored several extensive programs conceived to gain a knowledge as to what property changes might be expected when aircraft fluids are exposed to nuclear radiation. Essentially all fluid types have been irradiated in a reactor or pure gamma source and their property changes noted.

The scope of this paper is limited to radiation effects on aircraft turbine lubricants. However, the general approach to the problem of determining radiation effects has been very similar for other fluid types.

BRIEF HISTORY OF TESTING AND STATE OF THE ART

Notable among the radiation effects programs the Air Force has sponsored in the last few years was a program conducted by the Inland Testing Laboratories Division of the Cook Electric Company(1). About eighty-five conventional and special lubricants were tested by the use of specification bench tests and dynamic test equipment. Dynamic equipment included the WADC High-Temperature Bearing Head, the Ryder Gear Head, the WADC Deposition Tester, the Model "C" Panel Coker, and the Shell Four-Ball Wear Tester. The Inland Laboratories' 50,000-curie cobalt-60 source was used.

General conclusions drawn from the Inland Testing Laboratories program might be summarized:

(1) Lubricating oils are available which may perform satisfactorily to radiation dosages of about 10^{10} ergs/g (C).

(2) The most limiting factor, other than radiation, is the current factor limiting lubricant application in conventional engines, namely, temperature.

(3) The behavior of lubricants in dynamic test equipment cannot be predicted by preirradiating a sample of the fluid and then performing the test in the absence of radiation. This suggests that the combined effects are synergistic rather than additive.

(4) For specific lubricants, a radiation environment may intensify or lessen the effects of the thermal stress imposed by the test equipment.

(5) Different fluid properties do not necessarily indicate a change in a given lubricant simultaneously. That is, a lubricant might be "out of spec" as far as some properties are concerned long before other properties change.

(6) A cyclic effect is often present in property variations with increased dose.

Concurrent with the programs for evaluating conventional lubricants, the Air Force has sponsored a continuing effort for the development of new radiation-resistant fluids. As a part of this effort, the Shell Development Company has concentrated on the synthesis and evaluation of a very promising series of compounds, the polyphenyl ethers(2, 3). The compounds are characterized by a number of unique and desirable properties:

(1) Polyphenyl ethers are thermally stable to temperatures about 200 to 300°F higher than the best available synthetic lubricants.

(2) They are usable fluids over a wider temperature range (approximately 0-600°F) than available synthetic lubricants.

(3) They are inherently more stable to the effects of oxidation and ionizing radiation. This advantage allows for an increased exposure to radiation dose of about a factor of 10.

(4) Polyphenyl ethers display lubricating, load-carrying and heat-transfer characteristics comparable to conventional lubricants at temperatures above which conventional lubricants are unstable.

Unfortunately, the least viscous of the unsubstituted polyphenyl ethers will not flow below 32°F. Some nuclear aircraft engines under consideration may allow for the use of polyphenyl ethers through design provisions for constant heating of the oil. Other possible designs will require pumpability of the lubricant as low as -40 or -65°F. This requirement is encompassed by the MIL-L-7808 and MIL-L-9236 specifications.

A further requirement for the turbine lubricant is that prohibitive degradation of properties does not occur during the aircraft mission. Presently available diester and light ester-type oils will be at best only marginally acceptable in this respect due to the combined effects of temperature and radiation dose.

Use of specification oils under marginal conditions requires a detailed technology beyond that presently existing as to what properties will change and in what direction.

An engine designer may have several available lubricating oils that appear to meet the non-nuclear requirements anticipated. He also needs radiation-effects information in two general categories:

(1) Data showing which of the available oils, if any, have significantly better resistance to radiation.

(2) Detailed information on the more radiation-resistant oils showing the separate and combined effects of various nuclear and nonnuclear environments.

RELATIVE RATING OF AVAILABLE TURBINE OILS

Most of the work in which the author has been involved has been directed toward the rating of the various available turbine oils relative to each other.

As a part of this work, a series of irradiations have been conducted at the Nuclear Aircraft Research Facility, Convair-Fort Worth, on three representative aircraft turbine oils. The oils are identified as follows:

(1) A typical, high quality, sebacate base oil which meets the specification MIL-L-7808C.

(2) A complex ester-type oil considered to represent an intermediate (unwritten) specification between MIL-L-7808 and MIL-L-9236. This oil is identified as GTO-790.

(3) A light ester oil of a type qualified to MIL-L-9236B further identified as GTO-915.

The three oils are known to contain various property improvement additives, the amounts and composition of which are considered proprietary.

The irradiations of these three oils were conducted with the oil circulating in a Dynamic Test Loop located adjacent to the Ground Test Reactor. A static sample was irradiated simultaneously in a separate reservoir located inside the Dynamic Reservoir in each case. Three irradiations, one on each oil, were conducted with conditions held as nearly constant as possible. The bulk oil was maintained at approximately 300°F. A common dose rate of approximately 4.1×10^8 ergs/g (C)-hr gamma dose and 8.1×10^9 n/cm^2-sec (E>2.9 Mev) neutron flux was maintained. Each irradiation was approximately 20 hours in duration.

Figure 1 is a block diagram of the Dynamic Test Loop used in these irradiations. The components consist of a 7-gallon reservoir equipped with immersion heaters and cooling coils, an electric motor-driven oil pump, a 60-micron filter, a pressure relief valve, a restrictor valve, and plumbing necessary to construct a closed loop. It was not intended that the Dynamic Test Loop simulate an aircraft engine - whichit certainly does not. The purpose of the loop was to provide a simple means of imposing thermal stress and shear on a lubricant simultaneously with exposure to reactor irradiation. It is felt that property changes under these conditions were more realistic than those established in static irradiations alone.

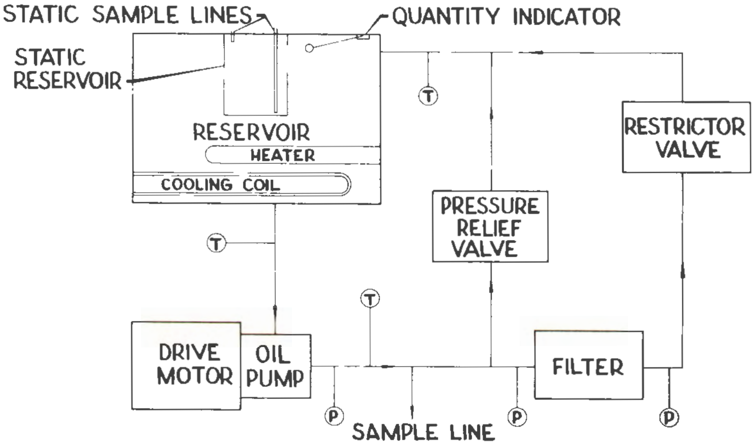

FIGURE 1. BLOCK DIAGRAM - DYNAMIC OIL-IRRADIATION RIG

Variations in damage between static and dynamic irradiations were more pronounced for the MIL-L-7808 than for the other two oils, but were evident in each case. In addition, separate samples of all three oils were circulated in the test loop for 20 hours in the absence of irradiation, and no appreciable change in the measure properties was observed. The control runs established that each oil was thermally stable at 300°F in the absence of irradiation.

During the three dynamic irradiations, the oil was sampled after the first hour and at the end of each two hours thereafter. Simple tests (viscosity, acid number, flash and fire points) were run immediately on each sample. This allowed for a constant check on some basic properties. Several more time-consuming tests were accomplished only on the control, 10-hour-irradiated, and final-irradiated samples. These tests included coking tendency (Model "C" Panel Coker), lubricity (Shell Four-Ball Wear) and oxygen absorption (Modified "Dornte" test). Oxygen absorption was also checked on some additional samples of MIL-L-9236 to better define the oxygen-absorption-rate curve.

All the measured properties changed during irradiation. Figure 2 shows the effects of irradiation on viscosity. Generally, one expects viscosity to increase - an increase which may be preceded, however, by an initial decrease, as exemplified by MIL-L-7808. In this case, the decrease was probably due to the immediate breakdown of high-polymer additives in the MIL-L-7808. Viscosity changes of the magnitude shown in Figure 2 would probably not affect the lubricating properties of an oil, provided that proper flow was not impeded. Table 1 shows the results of Shell Four-Ball Wear Tests on these oils. Changes in wear scars were slight and probably not significant.

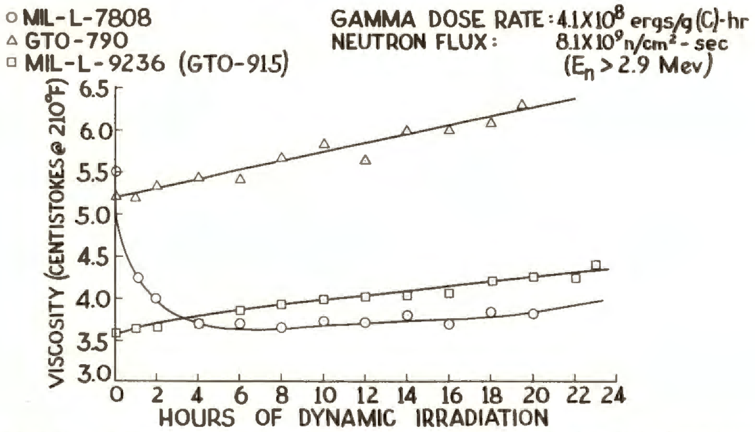

FIGURE 2. EFFECTS OF DYNAMIC IRRADIATION ON VISCOSITY

TABLE 1. EFFECT OF DYNAMIC IRRADIATION ON SHELL FOUR-BALL WEAR

(130°F, 1800 rpm)

Lubricant	Hours of Irradiation*	Wear Scar Dia.(mm) 20-kg Load	Wear Scar Dia.(mm) 40-kg Load
MIL-L-7808C	0	0.29	0.45
	10	0.35	0.45
	20	0.32	0.57
GTO-790	0	0.96	1.04
	10	0.70	1.01
	19.5	0.72	1.00
MIL-L-9236 (GTO-915)	0	0.69	0.73
	10	0.88	1.17
	23	0.77	0.85

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*Gamma Dose Rate: 4.1 x 10^8 ergs/g(C)-hr
Neutron Flux: 8.1 x 10^9 n/cm^2-sec
(E_n > 2.9 Mev)

One property which is very sensitive to irradiation is acid number. Figure 3 shows the changes in this property. The extent to which acid number reflects performance is not established, but it is certain that the acid build-up in these three oils is large enough to present a problem. This would be particularly true if the oils were in contact with machinery for extended times. Acid build-up was much more pronounced in the MIL-L-7808 than the other two oils.

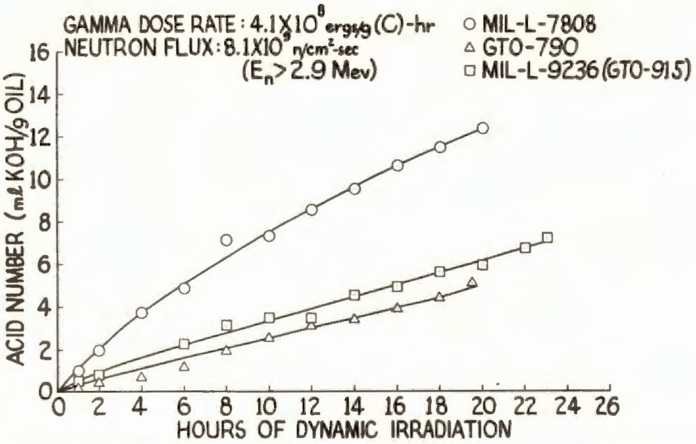

FIGURE 3. EFFECTS OF DYNAMIC IRRADIATION ON ACID NUMBER

A fair index to degradation is the rate at which oxygen is absorbed by an oil. Figure 4 shows the effect of irradiation on the oxygen absorption rate of GTO-790 and MIL-L-9236. The figure shows that a few hours of irradiation drastically reduces the stable life of the oils under the test conditions.

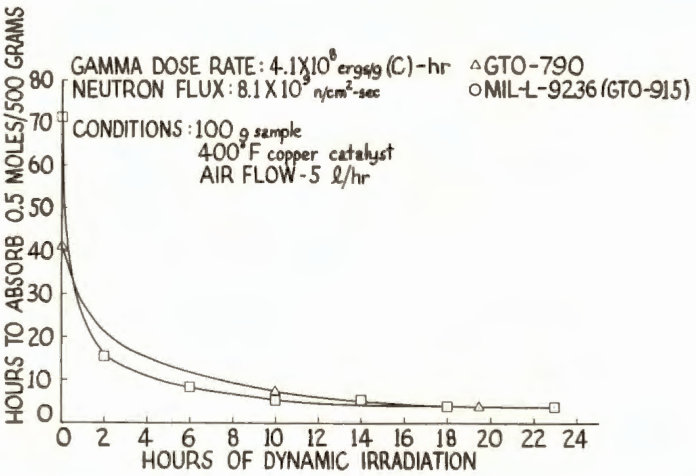

FIGURE 4. EFFECTS OF DYNAMIC IRRADIATION ON OXYGEN ABSORPTION RATE

This is concluded to be the result of the inactivation of oxidation inhibitors which are usually relied on heavily in synthetic oils. Unfortunately, oxygen-absorption-rate data on irradiated MIL-L-7808 are incomplete and are not included. Figure 5, however, indicates the oxidation stability of the three oils in the absence of irradiation. Stable life is plotted as a function of the reciprocal of absolute temperature.

The tendency of an oil to form coke when it is splashed onto a hot metal surface is important because of the hot spots present in all engines. Laboratory panel coking tests are inherently insensitive to small variations. They suffice, however, to differentiate between widely varying

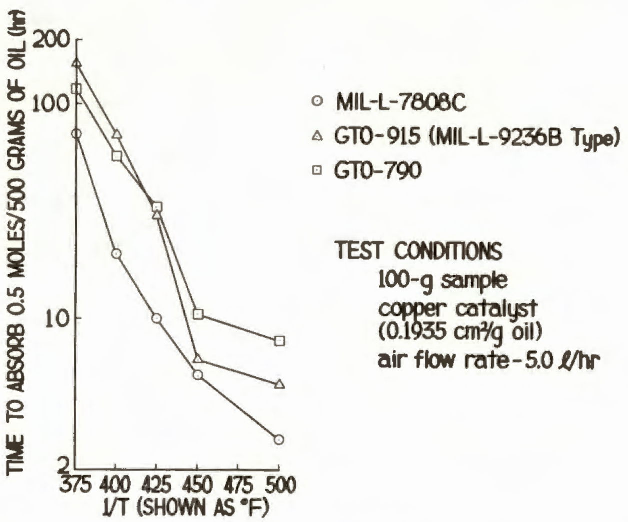

FIGURE 5. OXYGEN ABSORPTION RATE VS. 1/T

coking tendencies. Table 2 shows that the tendency to form coke at 600°F was drastically increased in the irradiated MIL-L-7808 samples. The coking changes in the other two oils probably indicate the loss through volatilitization of constituents which normally form coke.

During the dynamic-loop irradiations, the flash point of each oil was decreased approximately 100°F. Flash-point decreases almost always occur when oils are irradiated and must be monitored for safety purposes.

TABLE 2. EFFECT OF DYNAMIC IRRADIATION ON COKING TENDENCY

(Model "C" Panel Coker)

Lubricant	Irradiation*, (hours)	600°F Coke, mg	600°F Oil Used, ml	700°F Coke, mg	700°F Oil Used, ml
MIL-L-7808C	0	9	187		
	10	545	200		
	20	1635	200		
GTO-790	0	30	95		
	10	4	95		
	19.5	119	100		
MIL-L-9236 (GTO-915)	0	34	168	127	428
	10	5	190	22	485
	23	7	198	24	483

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*Gamma Dose Rate: 4.1 x 10^8 ergs/g (C)-hr
Neutron Flux: 8.1 x 10^9 n/cm^2-sec
($E_n > 2.9$ Mev)

Engine oils are sometimes used as hydraulic power media. An example of this is the use of MIL-L-7808 in the main and secondary nozzle actuators on some models of the J-79 engine. The evolution of gaseous products from a fluid in a hydraulic application would possibly affect the system response. Figure 6 shows the gassing rates for the three engine oils. Gassing data were obtained in separate experiments not utilizing the dynamic oil loop. The technique consisted of monitoring temperature and pressure in sealed irradiation containers. Classic, ideal gas formulae were applied to reduce the data to STP. The evolution of gas from an oil appears to be a linear function of absorbed dose when dose rate is constant.

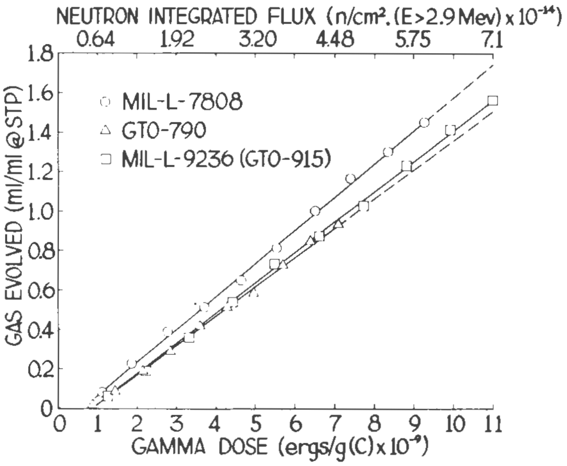

FIGURE 6. GAS EVOLUTION VS. RADIATION EXPOSURE

PREDICTING RADIATION DAMAGE

We have seen in the preceding tables and figures some of the ways in which exposure to reactor irradiation may affect aircraft turbine oils. As new oil classes are developed, similar irradiation will be conducted to rate the various oils relative to one another. It should be emphasized that at present these data cannot be used for other than comparison purposes.

Data obtained in test fixtures must eventually be evaluated on only one basis: that is, whether or not the data aid in a prediction of the lubricant's behavior in its intended application. The data presented in this paper will probably be deficient in this respect for at least two reasons:

(1) The dynamic test loop was not correlated with any specific application. The author knows of no instance in lubricant testing where a single test rig has been correlated with an aircraft turbine engine. It is therefore assumed that this limitation will be present in any screening program short of full-scale engine testing.

(2) It has been established that radiation-induced property changes in an oil cannot be predicted on the basis of the total accrued dose alone. The dose rate, test temperature, and the presence of other oxidation or shearing forces must also be considered.

Figure 7 shows the extent to which different dose rates may affect radiation damage to MIL-L-7808. This figure is a plot of acid number versus total accrued gamma dose for irradiation at three different dose rates. It is obvious that acid build-up is related to factors other than total dose, such as dose rate. Data for Figure 7 were obtained in three irradiations in the Dynamic Test Loop described earlier. The irradiation described previously for comparison with GTO-790 and MIL-L-9236 is represented in Figure 7 by the intermediate dose rate.

Figure 7 shows only the importance of dose rate in radiation effects. A temperature dependence and an interaction between temperature and dose rate have also been observed(4). Therefore, in order to predict property changes in an oil exposed to nuclear radiation, one must consider at least the dose, dose rate, the test temperature, and the extent to which oxidation and shearing forces are present.

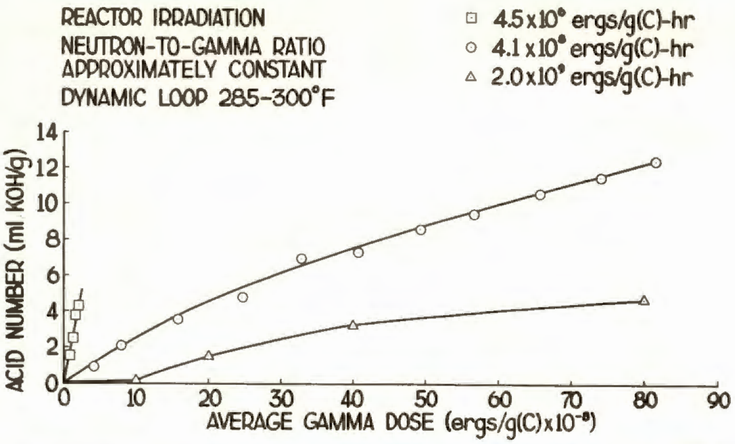

FIGURE 7. ACID NUMBER INCREASE IN MIL-L-7808 AT THREE DOSE RATES

Knowledge is required, not only of the separate effects of each of the above parameters, but also of the effects due to their interaction. Such information is required for development of a method whereby radiation effects data may be extrapolated beyond the specific conditions of a test. At the present no proven predictive methods exist. Recent emphasis on the need for such methods, however, should lead to progress in their development.

FUTURE REQUIREMENTS AND CONCLUDING REMARKS

The data presented on the dynamic irradiation of MIL-L-7808, GTO-790, and MIL-L-9236 (GTO-915) oils lead to certain conclusions, as follows:

(1) All three oils completed the dynamic irradiation without significant damage to the component parts of the dynamic test loop.

(2) The sample of MIL-L-7808C was somewhat more sensitive to radiation-induced property changes under the test conditions. The large increases in coking tendency and acid number form the basis for this conclusion. However, the test temperature (300°F) is much more severe for MIL-L-7808 oil than for GTO-790 or MIL-L-9236 type oils.

(3) Lubricating properties as measured by the Shell Four-Ball Wear Test were essentially unchanged in all three oils.

(4) No great difference was detected between the effects of the radiation on GTO-790 and MIL-L-9236 (GTO-915) under the test conditions.

(5) Exposure to nuclear radiation drastically reduces the stable life of inhibited turbine oils as measured by the Dornte oxidation test.

While the data presented in this paper provide a comparison between three general oil classes, it should be re-emphasized that only one set of operating conditions is represented. Extrapolation of these data to other conditions of dose rate, temperature, shearing stress, etc. should be avoided.

Future requirements for dealing with radiation effects in aircraft turbine oils will include:

(1) The development of predictive methods whereby data may be extrapolated beyond the specific test conditions.

(2) Irradiation testing in enough specific conditions to provide initial input to predictive methods.

(3) Fundamental studies which yield insight into the basic mechanism involved in radiation-induced property changes.

(4) The development of dynamic test devices which show correlation with engine tests and which might be adaptable to testing in a radiation field.

(5) Progress in many areas of such basic nonnuclear work as additive mechanisms, thermal and oxidative stability, corrosion mechanisms, and the agents of wear and lubrication.

LIST OF REFERENCES

1. Krasnow, M. E., Reynolds, O. P., and Wolford, O. C., "The Behavior of Fuels and Lubricants in Dynamic Test Equipment Operating in the Presence of Gamma Radiation," WADD TR 58-264, March 1959.

2. Mahoney, C. L. et al., "Nuclear Radiation Resistant High Temperature Lubricants," WADD TR 59-173, December 1958.

3. Borsoff, V. N., Beaubien, S. J., and Kerlin, W. W., "High-Temperature Lubrication in the Presence of Nuclear Radiation," WADD TR 60-424, June 1960.

4. Collins, C. G., "Combined Time, Temperature, and Radiation Effects on Organic Materials," Paper presented at the Third Semiannual Radiation Effects Symposium at Marietta, Georgia, 28-30 October, 1958.