

DISCUSSION

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In recent months, the addition of water to combustion systems has been the subject of numerous articles in the popular literature [7–12].⁶ This renewed interest has been stimulated by the invention of several “devices” for producing water-in-fuel emulsions, primarily for combustion in external systems, and by the claims of one of the inventors E. C. Cottell [13] that the use of his device provides major improvements in both emissions and energy utilization characteristics of practical combustion systems.

While several industrial evaluations have been mentioned in these articles and a more limited number of technical papers have been presented at various meetings [14, 15], the works of Hall appear to be the first external combustion results on water-in-fuel emulsions to be published in the open literature. Hall is also the first to have attempted complete documentation of both emissions characteristics and effects on energy utilization efficiency. However, intensive review of the subject [16–18] has led me to conclude for reasons summarized below that this work, as do other known results, falls short of quantitatively documenting the optimal combustion modifications achievable with the use of water-in-fuel emulsions. The preceding paper of this session [19] amply demonstrates that a number of relatively simple modifications of existing burner systems can also lead to similar improvements in carbon particulate emissions and thermal operating efficiency reported here. Thus, the question of what combustion of water-in-fuel emulsions accomplishes that cannot be done more economically through modification and/or adjustment of existing burner hardware remains unanswered.

The principal factor distinguishing the combustion of water-in-fuel emulsions from water addition through other means is a phenomenon termed “microexplosions” by those who first discovered it nearly twenty years ago [20]. Microexplosions such as those documented in Fig. 11 are a result of preferential vaporization of small water droplets dispersed within the fuel (internal phase). It is theorized that a properly formulated emulsion will produce microexplosions of sufficient violence to produce secondary atomization and micro-mixing within a spray of emulsified fuel droplets, thus reducing the level of heterogeneity that exists in most liquid spray combustion systems. Through mechanisms described elsewhere [17] microexplosions, therefore, reduce formation of large particulates and thermal NO_x . The additional benefit of localized charge dilution *within* the fuel rich region of the diffusion (mixing) limited combustion is also of significant consequence to reducing thermally formed NO_x and *gas phase* soot formation, and combined with the effects from the micro-explosions themselves, the process leads to improved emissions/utilization characteristics of the particular combustion system. Unfortunately, in contrast to internal combustion applications [17], addition of water to external combustion must result in an additional loss mechanism due to the efflux of the vaporized water (heat of vaporization) from the device. Without reduction in other losses, water-in-fuel combustion in external systems must therefore lead to decreases in thermal operating efficiency. However, reduced formation of carbon particulates (especially those of larger size) leads to decreases in the excess air required to meet the desired particulate emissions level. Thus, it is the functional dependence of the amount of water added to emissions levels and excess air required which primarily governs the magnitude and sign of changes in thermal operating efficiency. Previous investigators have not only recognized this fact, but furthermore have tacitly assumed that the internal phase ratio (volume percent of water in the emulsion) is the only emulsion

parameter important in optimizing emulsion combustion characteristics.

However, theoretical and experimental work at Princeton [21] has identified several other emulsion properties which must also be taken into account. First, it would appear that not only the amount of water, but the way it is distributed within the fuel droplets is important to optimizing the microexplosion phenomena (internal phase size distribution). The rates of heating and of phase change as well as the total volume change during vaporization are all important phenomena to be considered in selecting the correct internal phase properties. Confirming evidence for these hypotheses are currently available from at least two sources.

1. Current results of suspended droplet combustion tests at Guggenheim Laboratories indicate that by decreasing the internal size distribution of a water-in-Bunker C fuel emulsion from approximately 10 microns to around 1 to 2 microns significantly increases the time necessary to totally disrupt the primary fuel droplet.

2. A recent study [22] of the effects of emulsified fuel combustion on particulate emissions and primary zone radiation from a gas turbine combustor has shown that both the level of water content and surfactant loading of the emulsion have substantial effects on emissions reductions (Figs. 12 and 13).

The emulsions were formed using a Gaulin Model 110 Laboratory homogenizer operating at a constant pressure of 3000 psi. It was initially documented that addition of surfactant to the JP-5 reference fuel without water showed no effect on combustion emissions. At low surfactant concentrations, the stabilized internal dispersed phase size distribution reaching the combustor was determined by surfactant loading because there was an insufficient amount to support the total interfacial area of the internal phase size distribution produced at the homogenizer. As surfactant concentration was increased, larger interfacial areas could be supported and smaller internal phase size particles were produced. The curves of emissions approach asymptotic values at increased surfactant loading because the internal phase size distribution is then governed by the homogenization pressure. If homogenization pressure had been increased internal size distribution may have been further reduced. It is reasonable to suggest that at very small internal particle sizes such as those found in micro-emulsions [23], the material would behave as a multicomponent solution and the microexplosion phenomena would become insufficient to rupture the primary fuel droplet structure.

Contrary to the postulates of others [24], Fig. 13 suggests total flame radiation is reduced rather than increased by using emulsified fuels. Toussaint and Heap [15] also have reported similar observations for furnace combustion. Reduction in radiation is not surprising, since in diffusion (mixing) limited combustion continuum radiation from particulates is far more significant than spectral radiation from hot combustion gases.

From the patent literature [25, 26] it appears that neither manufacturer of the devices tested has considered any emulsion characteristics other than having the dispersed phase droplet size small in comparison to the atomized emulsion spray. It should also be noted that the TOTAL device depends on ultrasonic rather than high pressure mechanical effects to produce an emulsion. The ultrasonic energy produced by cavity/orifice plate resonance is probably of much lower intensity than that of the Cottell reactor. Yet, from fundamental principles, there appears to be no energy limit which if surpassed permits emulsion stability for long periods of time without the aid of chemical stabilizers. Residual oils themselves contain sufficient amounts of natural emulsifying agents for stabilization at room temperatures. However, once the energy necessary to form the emulsion is provided, the internal size distribution which is stabilized may only be modified by changing the amount of chemical emulsifying agent. Furthermore Barrett, et al. [27] have noted partial phase separation (breaking) of some natural residual oil emulsions at elevated temperatures well below the preheat levels used by Hall.

While not reported in the paper, Mr. Hall has stated in private communication that fuel oil and water preheats were held constant upstream of the emulsifying devices at 190 and 140°F, respectively. Thus emulsion preheat decreased from that of the pure fuel as larger

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⁶ Numbers in brackets designate Additional References at end of discussion.

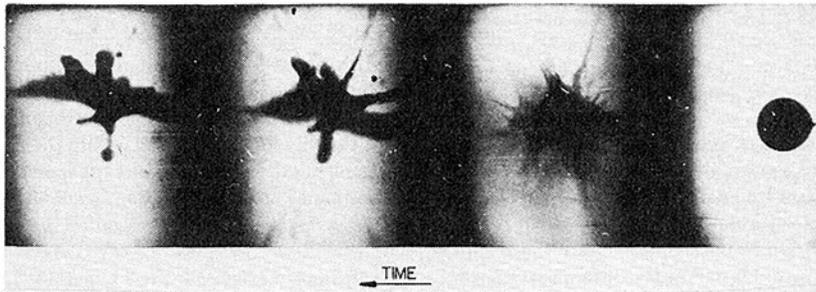


Fig. 11 16 mm high speed cinematography sequence of a burning droplet of 22 percent water-in-bunker C fuel emulsion (no added surfactant). Quartz filament (18μ) suspended droplet ignited with a small butane/air pilot flame. Initial droplet size, 350 microns. Internal phase *mass mean* size distribution approximately 10 microns. Camera framing rate, 5000 frames per s. Performed at Guggenheim Laboratories, Princeton University, Princeton, N. J. (Entire high speed film shown during oral discussion of this paper.)

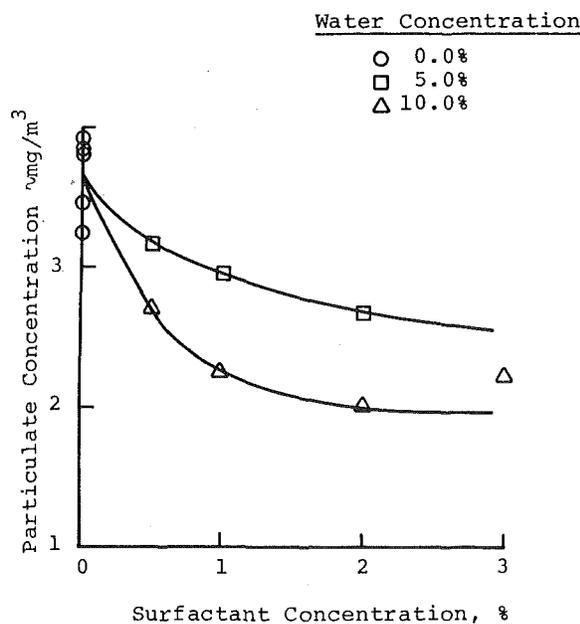


Fig. 12 Summary of effects of emulsion characteristics on the exhaust particulates at full power conditions for an Allison T-63 Gas Turbine Combustor—from reference [22]

internal phase ratio emulsions were formed.

Barrett, et al. [27] and Scherer and Trainie (reference [5]) have documented that the viscosity of water-in-fuel oil emulsions is considerably larger than that of the pure fuel, and is a function of internal phase concentration. Thus, Barrett, et al., concluded that fuel preheat temperature of residual emulsions must be increased to assure identical primary atomization for emulsions and pure fuel. Without such an adjustment secondary atomization from microexplosions must overcome reductions in primary atomization before any benefits can be realized. That changes in primary atomization of the order of magnitude which must have occurred here can cause substantial effects on particulate emissions was documented in a previous paper of this session. [19] It should be noted that according to Mr. Hall, no instructions suggesting the required variation in preheat were offered by the manufacturers of the devices tested.

In summary, because of the limitations in testing procedures and characterization of the emulsions, one must consider this work as a product evaluation rather than a quantitative study of the combustion characteristics of water-in-residual fuel emulsions. In this context,

Mr. Hall has produced a reasonable evaluation of two devices currently commercially available specifically for producing emulsions for combustion. However, a performance comparison of the devices must be further qualified by the variance in atomizer design used with each emulsifier.

It is not possible from these data to determine the minimum water required in emulsion to optimally effect the external combustion of conventional residual fuels. Some recent preliminary data [28] suggest that levels as low as 5 percent (by volume) may be sufficient. Thermal operating efficiency improvements may be several times those reported by Mr. Hall. However, it is clear from both Hall's data and

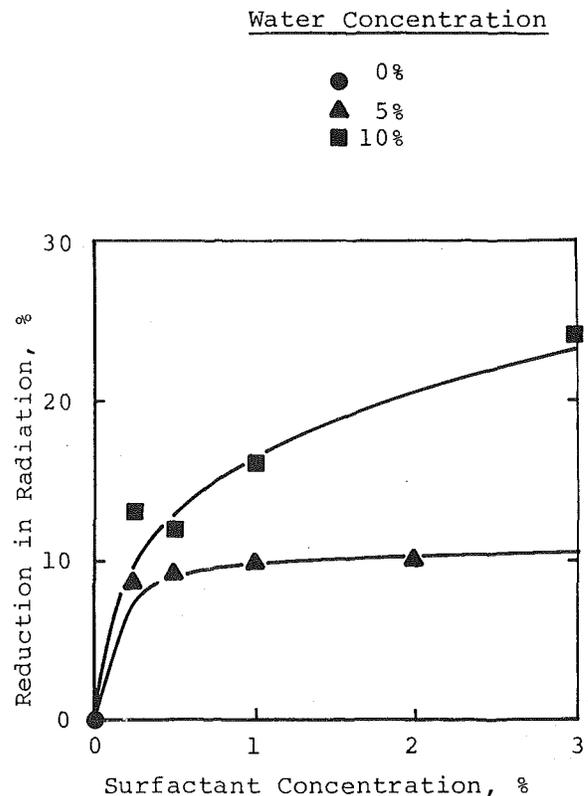


Fig. 13 Summary of effects of emulsion characteristics on the flame radiation at full power conditions for an Allison T-63 Gas Turbine Combustor—personal communication, Dr. C. A. Moses, US Army Fuels & Lubricants Laboratory Southwest Research Institute, San Antonio, Texas

fundamental principles that improvements as large as 20 percent (absolute) are impossible unless the external combustion system was initially operated far from optimum conventional design.

That simultaneous reduction of particulates and thermally produced NO_x can be achieved with emulsion combustion with improvements in thermal operating efficiency is a unique characteristic of emulsion combustion and deserves further research. Yet, perhaps the more intriguing prospect lies in simultaneous application of staged combustion and emulsified fuel technology. One might, thus, alleviate both fuel and thermally produced NO_x as well as particulates without increase in excess air requirements or degradation in thermal operating efficiency.

Additional References

- 7 Norbye, J. P., "Ultrasonic Fuel Reactor Gives Cleaner Exhaust, More Miles per Gallon," *Popular Science Monthly*, Nov. 1972, p. 22.
- 8 Lóf, G. O. G., "Water and Oil do Mix! And It Saves Fuel," *Science News*, vol. 104, 1973, p. 388.
- 9 Anonymous, "Oil and Water Alchemy," *Time*, Feb. 11, 1974, p. 31.
- 10 Westgate, R., "Mix Gas and Water for More Miles per Gallon," *Popular Science*, July, 1974, p. 108.
- 11 Immartino, N. R., "Can Water Help Fuel Burn?" *Chemical Engineering*, Nov. 1974, p. 84.
- 12 Ashley, M., "Using an Emulsion Gives a Small Boost in Burner Efficiency," *The Engineer*, Feb. 13, 1975, p. 39.
- 13 "Major Fuel Savings/Less Pollution Proved With the Cottell Ultrasonic Reactor," Tymponic Corp., Planview, N. Y., Tech. Bulletin 16, 1973.
- 14 References [4-6] this paper.
- 15 Toussaint, M., and Heap, M. P., "Formation of Oxides of Nitrogen and of Particles in the Flame of an Emulsion of Heavy Fuel and Water," presented to the Chemistry Commission of the International Flame Research Foundation, IJmuiden, Oct. 1974.
- 16 Dryer, F. L., Doohar, J., Hooker, P., Prosperetti, A., and Marsden, S., Section 3, Emulsified Fuels, *The Role of Physics in Combustion*, an APS

Summer Workshop, July; published in an *AIP Conference Proceedings*, Vol. 25, 1975.

17 Dryer, F. L., "Fundamental Concepts on the Use of Emulsions as Fuels," Aerospace and Mechanical Sciences Report No. 1224, Princeton University; presented at the Joint Western/Central Section meeting of the Combustion Institute, San Antonio, Texas, Apr. 21, 22, 1975.

18 Dryer, F. L., "Water Addition to Practical Combustion Systems—Concepts and Applications," Sixteenth International Symposium on Combustion, Massachusetts Institute of Technology, Cambridge, Mass; to be held Aug. 15-21, 1976.

19 Laurendeau, R., Hersh, S., and Dusatko, G., "The Reduction of Particulate Emissions From Industrial Boilers by Combustion Optimization," ASME Paper No. 75-WA/APC-3, presented to the Air Pollution Control Division of ASME, Winter Annual Meeting, Houston, Texas, Dec. 3, 1975.

20 Reference [1] this paper.

21 Dryer, F. L., Glassman, I., and Naegeli, D. W., "Fundamental Combustion Studies of Emulsified Fuels for Diesel Applications," Princeton University, Princeton, New Jersey, Apr. 19, 1974; initiating proposal to the Division of Advanced Energy Research and Technology, National Science Foundation. Grant No. GI 44215, initiated July 1, 1974 and renewed Jan. 1, 1976.

22 Moses, C. A., "Reduction of Exhaust Smoke From Gas Turbine Engines by Using Fuel Emulsions," Paper No. 75-18; presented at the Western States Section Meeting of the Combustion Institute, Palo Alto, Calif., Oct. 20, 21, 1975.

23 Lissant, K. J., "Micro Emulsions, Emulsions and Emulsion Technology," *Surfactant Science Series*. Marcel Dekker, Inc., New York, Vol. 6, Part I, Chapter 3, 1974.

24 Doohar, J., et al., "Emulsions as Fuels," ASME paper No. 75-WA/FU-3, presented to the Fuels Division of the ASME, Winter Annual Meeting, Houston, Texas, Dec. 3.

25 Patent No. 3,809,372, "Devices for the Generation of Ultrasonics and Their Application to the Preparation of Emulsions," Assignee Compagnie Francaise De Raffinage, Paris, France, May 7, 1974.

26 Patent No. 3,749,318, "Combustion Method and Apparatus Burning an Intimate Emulsion of Fuel and Water," E. C. Cottell, July 31, 1973.

27 Barrett, R. E., Moody, J. W., Hazard, H. R., Putnam, A. A., and Locklin, D. W., "Residual Fuel Oil Water Emulsions," Summary Report on Contract No. PH 86-68-84, Task Order No. 16, Battelle Memorial Institute, Jan. 12, 1970.

28 Personal Communication, R. Kinney, Gaulin Corporation, Everett, Mass.

U. Bonne⁷

This discussion is going to focus on three aspects of energy and operating cost savings due to external combustion of fuel oil-water emulsions:

- 1 those discussed in Mr. Hall's paper;
- 2 energy savings predicted via flue loss method;
- 3 recommended future work.

1 As a result of Mr. Hall's study, no doubt remains that emulsions reduce the emission of particulate mass loading of flue gases, in spite of relatively small changes in NO (total NO_x not given), CO and hydrocarbons. However, the energy savings of adding water to hydrocarbon fuels in external combustion systems are expected to be low, since volumetric expansion or generation of mechanical work, as in internal combustion engines is not the issue. Exact definition of the reduction of energy consumption or boiler operating costs, although beyond the main emphasis of the study, can, to some extent, be derived from the provided data, of which Table 3 provides a brief summary and clarification. The purpose of emphasizing this here stems from the belief that this is necessary information to anyone considering implementing the use of emulsified fuels. The author chose to adjust the combustion air, after adding the water, to match the Bacharach smoke number rather than the smoke mass loading. This is why the combustion air had to be increased with the Total device, leading to an increase in excess air losses and a decrease in particulate mass losses. Table 3 shows how large the efficiency gains and fuel savings would be according to the author, rows 15 and 16.

2 The provided data can, on the other hand, be used to arrive at efficiency gains by analyzing the change in flue loss component. Fig.

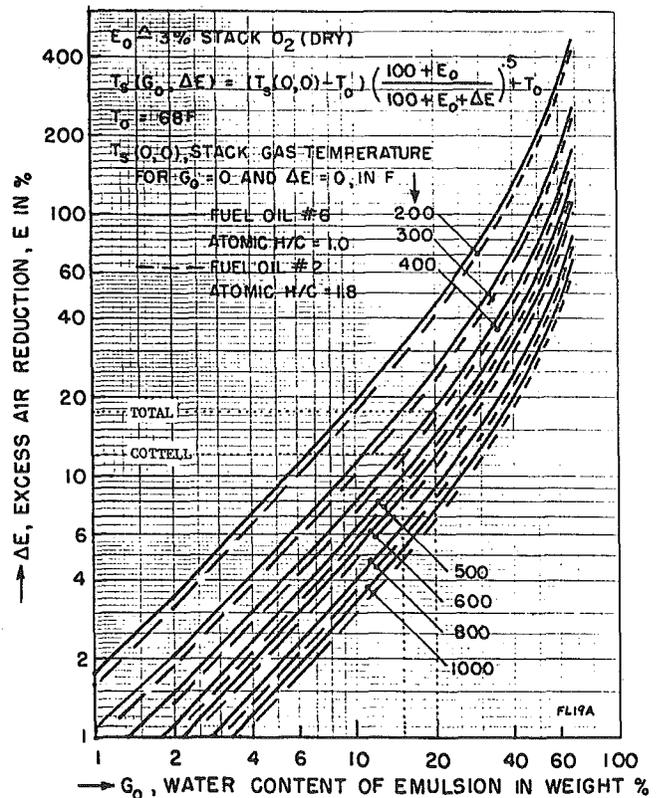


Fig. 14 Excess air reductions required for combustion of oil-water emulsion fuels in order to maintain equal combustion efficiency with respect to fuel oils alone—temperature reduction credit included

⁷ Honeywell Inc. Corporate Research Center Bloomington, Minn.

Table 3 Comparison between Cottell and Total Emulsifiers. North American packaged Scotch boiler rated at 2.64 GJ/hr (2.50·10⁶ Btu/hr) and fired at 97.5 percent of rating. Residual fuel oil of 44.45 MJ/kg (19,110 Btu/lb) HHV.

Parameters	Units	Emulsifiers	
		Cottell	Total
<u>Baseline</u>			
1 Combustion air, A/flue CO ₂	% of stoich./%	145/10.4	136/10.6
2 Flue gas temperature net rise	F	331	318
3 Flue losses (recalculated)	%	15.58/15/75	14.67/15.20
4 Particulates: Mass loading	mg/m ³	91@A = 147	173@A = 135
5 Bacharach No.		5.6@A = 145	4.7@A = 134
6 Combustion Air	% of stoich.	120	146
7 Flue gas temp. net rise(1)	F	318	338
8 Particulates: Mass loading	mg/m ³	60@A = 147	66@A = 135
9 Reduction to	%	63@A = 147	38@A = 135
10 Reduction to	%	84@A = 119	
11 Bacharach No.		5.6@A = 120	4.3@A = 146
<u>Optimum Emulsion at water content</u>			
12 Emulsifier power consumption	wt % watts	15 575	20 ?
13 Prime fuel rate equiv.	% of fire	.222	cos φ*
14 Relative costs (2X prime fuel)	% of fire	.444	
15 Efficiency gain	%	.89—1.68	1.79
16 Fuel savings	%	1.05—1.98	2.11
17 Operating cost savings	%	.61—1.54	< 2.11
18 Max. cost of emulsification equipment for 3 year payback (no interest)	\$	382—965	< 1322
Efficiency gain due to changes in:			
19 Fuel water content	%	-1.10	-1.57
20 Combustion air	%	1.43	- .59
21 Flue temperature rise	%	.39	- .57
22 Particulate mass	%	≅ .01	≅ .2
23 Total	%	.73	-2.53

* a value of cos φ = .8 was assumed.

14⁸ shows a family of curves corresponding to the amount of combustion air reduction, for the amount of water in the emulsion, required to maintain efficiency constant. Fig. 14 is based on the finding⁹ that at constant firing rate (Btu/hr), increases in the water content of emulsions does not lead to increases in flue temperature. Fig. 14 can be of help to determine when to use or not to use emulsified fuels. A simple enthalpy balance calculation shows that air reductions required to break even under the conditions of Hall's experiments are

⁸ Bonne, U., "External Combustion of Fuel Oil-Water Emulsions," Honeywell Inc., CRC, Apr. 14, 1975; to be presented at 1976 ASHRAE Annual Meeting, Dallas, Texas, Feb. 1976.

12 and 17.7 percent, respectively, as shown in Fig. 14. A breakdown of the changes in flue loss components due to fuel water content, excess air, flue temperature changes,⁹ and particulate mass are listed in Table 3, rows 19-22. The sum of these (row 23) should agree with row 15. As shown, good agreement is obtained only for one set of data.

3 It appears that more experimental data on the reduction in excess combustion air achievable as a function of (emulsified) water additions and emulsification equipment are needed in order to: more completely assess the benefits, describe the effect of water droplet size in the emulsion, and pinpoint the optimum operating conditions. Work underway at Princeton University¹⁰ and consideration of hardware alternatives such as conventional homogenizing equipment¹⁰ should provide interesting new insights. Water droplet sizes in the emulsions were not measured in the present study but it appears that pressure atomization resulted in larger soot particles, but similar combustion efficiencies, if the two devices had been operated on the basis of equal mass loadings, corresponding to similar combustion air in the pure fuel runs. Another aspect of this picture will be provided by the measurements of the long term effect of fouling of heat transfer surfaces. Operating boilers at equal flue particulate mass loadings but reduced particle size (due to the effect of the emulsion) may well reduce the rate of soot deposits and I am looking forward to the results of the work Hall said is under way.

Author's Closure

Dr. Dryer stated that "this work, as do other known results, falls short of quantitatively documenting the optimal combustion modification achievable with the use of water-in-fuel emulsions." This statement is true but it is not germane to the EPA study since the purpose was to evaluate the effect on emissions and efficiency of two commercially available water/oil emulsion devices. The fact that the manufacturers of these devices did not optimize the emulsifiers is not the fault of the EPA. It was not the intent of this study to develop a commercially available product for a manufacturer. A more fundamental study of the water/oil emulsion process would be useful and may result in some further reduction of particulate mass emissions and may provide some additional increase in efficiency. The subject study does give the direction of change and a reasonable idea of the magnitude, as was intended.

In reference to Dr. Dryer's comment about the need for surfactants to produce a stable emulsion, tests were run using the Cottell Reactor and the Total emulsifier without surfactants. If there was a phase separation it did not affect the combustion process to any noticeable degree. Our experience has shown that surfactants are only necessary when firing distillate oil. Also, the use of surfactants was not recommended by either manufacturer for firing water/residual oil emulsions.

Dr. Bonne stated that he is looking forward to the results of work by industry and other government agencies in which an evaluation is being made on the effect of emulsions on efficiency for a long term due to reduced particulate deposits on heat transfer surfaces. Unfortunately, one such test which was being conducted by the Department of Defense has been cancelled due to equipment problems.

In Table 1 of Dr. Bonne's discussion in item 18, the "maximum cost of emulsification equipment for 3-yr payback (no interest) for the Cottell Reactor appears low and the figure listed for the Total emulsifier appears much too high. According to Crest Ultrasonics the Cottell Reactor tested by EPA costs 5500 dollars plus an installation charge. This includes a guarantee on parts and service for 1 yr. According to D. S. Volkmar, the Total emulsifier is not an "off-the-shelf" commercially available item but can be specially ordered from Compagnie Francaise de Raffinage for less than 500 dollars.

⁹ Hall, R. E., EPA, private communication, Mar. and Nov. 1975.

¹⁰ Dryer, P. L., Princeton University, private communication, June 1975.