GEAP-4026

IN-CORE INSTRUMENTATION DEVELOPMENT, FIRST
TOPICAL REPORT, TASK II, PHASE I —TELEMETERING

By
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March 15, 1962

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San Jose, California

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REACTOR TECHNOLOGY

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FIRST TOPICAL REPORT, TASK II, PHASE I
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by

A. C. Duckart

March 15, 1962

**U. S. Atomic Energy Commission
Contract AT(04-3)-189
Project Agreement No. 22**

ATOMIC POWER EQUIPMENT DEPARTMENT

GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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SECTION I

INTRODUCTION

The purpose of this program is to investigate and develop means for efficiently obtaining data from within the core of a reactor by a form of telemetering. The development of such a telemetering system will make it possible to transmit information from 100 or more in-core sensors through a single pressure vessel penetration. This would result in considerable savings in pressure vessel design, signal transmission cables, enclosure penetrations, and signal conditioning equipment.

At present, each in-core sensor signal is brought out of the pressure vessel by means of a mineral-insulated, steel-jacketed cable, usually through individual penetrations. The sensor signal then goes to a junction box which is connected to a flexible cable, and from there the signal goes to the control room converters and indicating instruments. With a multiplexer in the pressure vessel, many in-core measurements can be performed using one pressure vessel penetration, one signal cable, and possibly one signal conditioner, amplifier, or converter.

The use of telemetering is common and widespread, but in this case the extremes of operating environment present development difficulties. The system must reliably operate unattended in a reactor vessel environment of temperatures to 700 F or more, and neutron and gamma fluxes approaching 10^{10} nv and 10^6 r/hr, respectively.

Phase I of this program will cover the development and construction of a working laboratory bench model of the in-vessel portion of a telemetering system. The model will be constructed of components suitable for use within a reactor vessel.

Phase II will be concerned with the fabrication and actual temperature testing of a prototype system. The final design will utilize the information gained in Phase I of this program. The readout portion of the system will be designed.

SECTION II

SUMMARY

To reduce the complexity and expense of making in-core measurements, a telemetering system is being developed that will greatly increase the information density of each signal cable penetration, and will result in fewer pressure vessel penetrations and fewer signal cables.

The primary effort of this phase is being devoted to the development of a multiplexing subsystem for use within the reactor pressure vessel. Developmental goals for a prototype include reliable operation for one year in reactor environments of 700 F or greater, and 10^{19} nvt thermal neutron exposure. However, the severe environmental conditions of temperature and nuclear radiation, coupled with the necessary reliability over extended periods of operation, have created development problems.

The most promising methods of multiplexing are (1) electromechanical commutation, and (2) electronic frequency division.

1. Electromechanical Commutation

With this method, a sampling switch, driven by a suitable prime mover, scans many inputs sequentially and couples them to a transmission line. At the receiving end, another switch is

driven in synchronism with the in-vessel switch, and couples the signals to their appropriate readout channel.

Electromechanical commutation has an advantage because of its simplicity, low noise level, and cost. On the other hand, the mechanical wear restricts useful life and reliability.

2. Electronic Frequency Division

With this method, each sensor controls a separate subcarrier oscillator, which is varied in amplitude or frequency by the input. The subcarrier oscillators are spaced in frequency and are linearly added to a common transmission line. At the receiving end, bandpass filters separate the various signals into their respective channels for demodulating and display.

Frequency division has the advantage of being purely electronic, and affords simultaneous transmission of all data rather than sampling; but such a system is comparatively complex and has a rather high noise level, it requires fairly elaborate receiving equipment, and it is normally limited to about 20 channels per transmission link. However, a system (TIMM) is being evaluated that will allow up to 200 channels per transmission link.

It is felt that the advantages of both methods are sufficient to warrant the continued development of each, in order to be able to make comparative evaluations of accuracy, cost, and reliability. At the present time, it is planned to build and test bench models of both types of multiplexers.

Phase II of this program will cover reactor tests of a telemetering system, and will compare its output with measured input signals, ambient temperature, neutron flux level, and elapsed time.

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SECTION III

DEFINITION OF TASK

3.1 System Objectives

1. System should have possibilities for substantial monetary savings over present methods of obtaining in-core data.
2. Signal cable penetrations through the reactor pressure vessel should be reduced.
3. Detectors, cables, and multiplexer should be replaceable without disturbing the reactor fuel.
4. System should not appreciably impair the reliability of in-core sensors.
5. Temperature, radiation, and pressure effects must either be negligible or compensated for.
6. The system should be more accurate than the detectors.
7. Crosstalk between channels should be negligible.

3.2 Performance Specifications

The following operational specifications represent standard criteria for measuring the worth of a telemetering system, and therefore are chosen as development goals for this task.

1. Linearity - For a given ramp input, the output must reproduce a ramp within 5 per cent from zero to full-scale values.
2. Sensitivity - The magnitude of the readout must represent the detector signal within 2 per cent of full scale. It is preferable that this specification hold for input frequencies from 0 to 5 cycles per second, although it is not a strict requirement in this application.
3. Repeatability - The system must develop the same output to within $1/2$ per cent of full scale for a steady input after the input has been changed (including 2X overrange) and then returned to its original value.
4. Hysteresis - The difference between outputs for a given input for increasing or decreasing inputs should not exceed $1/4$ per cent of full scale.
5. Reproducibility - The drift over a period of time of measured values under identical conditions should not exceed 5 per cent of full-scale values. This includes zero drift and span drift between calibrations, which could be monthly.
6. Resolution - The minimum distinguishable magnitude change shall be less than $1/4$ per cent full-scale value.
7. Life - The life of the system shall be at least one year. Components that could fail within this time should be replaceable. Individual component failure shall not affect the entire system.

but only its associated channel. Conservative ratings on components shall be used to minimize failure.

3.3 Environment

The following conditions are characteristic of the Vallecitos Boiling Water Reactor (VBWR) and are considered typical of boiling water reactors, except for temperature and pressure. Testing at temperatures in excess of 550 F will be accomplished by the use of electric heaters.

1. Temperature

In-Vessel - 80 F to 550 F (545 F normal)

Enclosure - 40 F to 120 F (70 F to 90 F normal)

Control Room - 70 F

2. Humidity

In-Vessel - saturated steam-water

Enclosure - 50 per cent to 98 per cent RH (90 per cent RH normal)

Control Room - 20 per cent to 90 per cent RH (50 per cent RH normal)

3. Pressure

In-Vessel - atmosphere to 1000 psia (1000 psia normal)

Enclosure and Control Room - one atmosphere

4. Nuclear Radiation

In-Vessel

Top of Fuel: thermal neutrons - 1×10^{13} nv

epithermal neutrons - 5×10^{13} nv

fast neutrons - 1×10^{13} nv
gamma - 10^9 r/hr $\left(\frac{dN}{dE}\right)_{\gamma} \approx 2$ mev)

Top of Steam Dome: thermal neutrons -

1×10^8 to 1×10^9 nv

fast neutrons - 2×10^8 to 2×10^9 nv

gamma - 10^6 to 10^7 r/hr

Enclosure - negligible, less than 1 mr/hr gamma

Control Room - negligible

5. Salt Spray - negligible
6. Fungus Growth - negligible (however, protection advised for exposed enclosure equipment)
7. Magnetic Fields - stray 60-cycle pickup probable in enclosure and control room; shielded cable reduces pickup to less than 100 microvolts for 200 feet of signal cable.
8. Vibration - in-vessel parts exposed to the coolant flow vibrate at their natural frequency (for example, an 18-inch steel rod oscillates at 28 cps in the longitudinal mode)

3.4 Input Signals

Insofar as possible, the system will be built to handle any of the standard in-core sensors, with preference given to sensors developed under Task I of this program (In-Core Power Monitoring). Thermocouple inputs will be the most difficult to handle because of their

millivolt signal levels. Ion chamber and resistance elements are quite easy to work with, since signal levels can be made to fall in the volts region. If ion chamber and resistance elements are measured with the same system, inputs will be adjusted to common span. Thermocouples will be considered separately. One solution under consideration for thermocouples is a d-c amplifier within the vessel. This would bring the signals up to the desired voltage for multiplexing.

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SECTION IV

AREAS OF INVESTIGATION

4.1 Configuration Within Pressure Vessel

Sooner or later, any kind of electronic multiplexing equipment will need servicing or replacement. Moreover, the equipment cannot be allowed to interfere with normal reactor work, and must be protected during core maintenance and fuel moves. Therefore, it was decided that the multiplexing unit should be housed in a stainless steel container and installed in an accessible, but out-of-the-way, location within the pressure vessel.

Such a location is the vessel wall just below the head. This location would allow easy access when the head is removed, and yet not be in the way for core maintenance. Signal cables to and from the multiplex unit can be brought down the vessel wall to the top of the core and installed between channels at the top of the core, permitting fuel moves with minimum disturbance to signal cables.

Use of connectors is possible for most kinds of detectors. These would provide replacement of detectors, cables, and multiplex unit without disturbing the entire system. A discussion of connectors is contained in Subsection 4.2.

Penetration of the vessel wall will be accomplished with a special stainless steel "O"-ring-sealed plug, approximately 1 inch in diameter.

Mineral-insulated cables to and from the multiplex unit will be brazed into this plug. Such a plug will accommodate 100 or more multiplexed signals, plus power for the multiplexing equipment.

4.2 Coupling to Detectors

Detectors should be replaced without disturbing the multiplexing system or cabling, if possible. This requires the use of a connector that is easily assembled and disassembled. Several types have been considered, and a discussion of those types follows.

4.2.1 Non-Hermetic

This involves the use of a connector that is made up in the reactor vessel, with no effort made to isolate the contacts from the coolant. Here two basic problems exist: (1) corrosion buildup on the contacts, and (2) film buildup on the insulators.

Laboratory evaluations were performed using both tap water and distilled water at temperatures up to 200 F. Contact corrosion was found to be slight when using silver-plated copper contacts; however, it could create a problem at elevated temperatures.

Film buildup on insulators was found to be a serious problem. When tap water was used, resistance dropped from 30,000 ohms to 500 ohms after two days immersion. No significant improvement was noted when distilled water was used.

It was noted that when the connector was removed from the water and dried with an electric heater, insulation resistance reached 2×10^9

ohms in about 20 minutes. From this test it was concluded that this type of connector would be unsatisfactory for ion chambers and resistance thermometers. However, low-resistance (less than 10 ohms) thermocouples or thermopiles might utilize this connector very well if thermal emf's at the contacts could be made negligible.

4.2.2 Hermetic

This is a connector which is sealed from the coolant media after it is made up. Two problems evident here are: (1) maintaining a good seal, and (2) connector makeup in the reactor.

The connection can be sealed by placing it inside a modified stainless steel tubing union. The connection could be made up under water if a means to dry the internals were provided. This suggested the use of a connector in which the internals are vented outside the reactor, either to atmosphere or through a vacuum pump. In this way the connector could be made up under water, be dried with a vacuum pump, and then maintained dry by the heat of the reactor.

Another possible way to make up connectors under water is to use a diving bell type (inverted cup) connector. In such a connector, the cup is filled with air and lowered over the contacts, forcing water expulsion during makeup. A small saturated gas volume is present in this connector; however, any temperature increase would reduce the relative humidity.

4.2.3 Inductive

This type involves the use of a transformer coupling to the detector. Encapsulated coils could be slipped over a 400-series stainless-steel post to increase the coupling efficiency. In addition, the hollow bobbins of each coil could be made of magnetic material. The main concern is the radiation effects of the magnetic material. Available literature and experience with in-core magnetic pickups reveal that permeability of some magnetic materials is reduced considerably after exposures in excess of 10^{19} nvt.

4.2.4 Optical

An optical fibre vendor was contacted concerning possible coupling and transmission of data by means of light. This approach was dropped because of the required detector complexity and lack of data on radiation effects on optical fibres.

4.3 Multiplexing

Multiplexing is the transmission of two or more messages at the same time over the same interconnecting link. Present practice is limited to the use of one of two basic methods - time division multiplexing or frequency division multiplexing.

Time division involves the sequential switching of two or more signals into a common transmission link, another switch at the receiving end to couple signals back to their respective readout devices, and a means of synchronizing the two switches. Such switches are generally called commutators, regardless of whether they are mechanical or electronic, because they can be represented by rotating selector switches.

Frequency division multiplexing involves a separate subcarrier oscillator for each input, with subcarrier spacing in frequency. Transmission of all channels is continuous, with linear addition of all subcarrier frequencies onto a common line. Each input modulates its own subcarrier by varying the frequency, amplitude, or phase. At the receiving end, frequency selective circuits and demodulators are used to return the signals to their proper readout channel.

4.3.1 Circuit Sharing With a Grid

The grid would be formed by two layers of parallel conductors, with the wires of one layer perpendicular to the wires of the other layer. At each intersection of conductors, a detector would be placed, connecting across the two intersecting cables. By applying an appropriate voltage on one cable and measuring the resulting signal on the other, a measurement of a particular detector is obtained. In this way, a sensor can be located at the intersection of every cable in the grid, with the result that N cable pairs can be used to measure N^2 separate sensors. Use of such a scheme requires that measures be taken to eliminate crosstalk between parts of the grid. It has been established that if all conductors opposite the powered lead are held at the same potential during a measurement, no crosstalk is possible. This is shown schematically on the following page, for a simple model. Resistance type detectors are shown at the intersections.

It can be seen from the schematic that as long as points "a", "b", "c", and "d" are held at the same potential, no interaction is possible. However, if point "a" is at a different potential than "b", "c", or "d", current flow is possible through the "2", "3", and "4" legs, resulting in an erroneous indication at "a". With the scheme shown, V is adjusted to give a null in the galvanometer "g". This results in the equation

$$i = \frac{V}{R_x} = \frac{E}{R_1} \quad \text{or} \quad \frac{V}{E} = \frac{R_x}{R_1}$$

Since the quantity R_x/R_1 can be made to represent reactor power levels, the quantity V is directly proportional to power level. (The quantity $R_x - R_1$ can be measured with a slightly different bridge configuration.) Similarly,

resistance elements could be replaced by ion chambers. However, in this case, E would become the variable voltage so that

$$\frac{V}{R_x} = \text{ion chamber current} = \frac{E}{R_1}$$

In this case, E is directly proportional to chamber current which, in turn, is proportional to power level. In either case, the null balance detection and voltage variation can be accomplished electronically in less than one millisecond.

The operation of a grid system necessarily used time division multiplexing, as pointed out by the above schematic. Electronic null balancing is necessary if high scanning speeds are to be realized. The system shown below was evaluated in the laboratory and found to be satisfactory for readouts of up to 1000 points per second.

The previously-stated equation, $\frac{V}{E} = \frac{R_x}{R_1}$ will be valid as long as the output impedances of the ramp generator (V) and the d-c supply (E) are small, compared with R_x and R_1 . Since V is a ramp, it may be expressed as $V = kt$, where k is the slope of the ramp in volts per second, and t is time in seconds. This results in: $t = \left(\frac{E}{k} \frac{R_x}{R_1}\right)$. E and k are both adjustable at will. If $\frac{R_x}{R_1}$ is proportional to reactor power, then it can be made to read power level by adjustments of E or k.

Detector scanning can be accomplished in either of two ways. In the first way, both sides of the grid (power and measurement) can be brought out of the reactor and the scanning done out of the vessel. This would give the most reliability to the system. Enough cables for 144 detectors (24 signal leads) can easily be brought through a single 1-1/2-inch vessel penetration plug. In the second way, the scanning could be done within the pressure vessel by means of an electromechanical sampling switch, similar to that described in Subsection 4.3.2.

4.3.2 Electromechanical Commutator

The simplest method of achieving signal cable reduction is probably by the use of an electromechanical sampling switch. With this device, all signals are brought to the switch, and the wiper brush sequentially scans them at some fixed rate. At the receiving end, a decommutating switch couples the signals back into their respective readout or recording channel. This requires an accurate means of maintaining exact synchronism between the scanning and the decoding switches, which is normally done by means of a synchronizing pulse originating from one

or more positions on the scanner and decoder. If these pulses do not occur simultaneously, an error signal is developed which is proportional to the angular error between the brush positions of the two switches. The lagging switch is then sped up until the error signal disappears.

Normally, one switch is driven more slowly than the other (for the same voltage) so that a constant error is present. This eliminates overshoot and hunting. In order to meet the requirement of long life at elevated temperatures, a rather slow scan speed is dictated. Minimum life of one year at 700 F and continuous operation require a maximum of 1 revolution-per-second brush speed. This slower speed also ensures that noise will not exceed 25 to 50 microvolts, which could be quite important for thermocouple-type detectors.

An alternate to the brush-type commutator is the sequential closing of dry reed switches with a rotating magnet. This approach would eliminate much of the contact wear present in the brush types and allow replacement of the encapsulated contact capsules. Scan speed improvement is possible due to the short pull-in and drop-out times required for the reed. Still, 1000 contacts per second would be the fastest sampling speed one could expect. However, predicted life is about 10^8 operations per switch at elevated temperatures. This imposes a limit of about 100 points per second (one complete scan per second) if one year's continuous operation is expected from such a device.

4.3.3 Electronic Multiplexing

Electronic multiplexing involves the acquisition and transmission of multiple inputs without the reliance upon mechanical contact closures. Commonly used methods include:

1. Sequential switching of inputs to a common transmission line.
2. Subcarrier frequency spacing of inputs, with each input controlling its subcarrier oscillator.
3. Common subcarrier frequency for all inputs (but sequentially-scanned inputs vary amplitude, duration, or frequency of the subcarrier oscillator).

From a reliability standpoint, time division multiplexing systems must be carefully designed if operation is serial; that is, failure of one component in a string should not impede the transmission of data inputs other than those directly affected by the failure. However, if the probability of failure of a critical component is extremely remote, then there is no reason why serial operation cannot be considered, since higher information density is possible with such a system.

Generally, information densities can be four or five times higher with a time division multiplex than with frequency multiplex schemes. Frequency division multiplexing has much greater system reliability, since the loss of one channel results only in loss of data for that channel. Other advantages include continuous transmission of data on all channels, and lack of need for precision synchronizing circuits; however, signal density is limited to about 200 channels per transmission link.

The most promising electronic multiplexing methods for this application are: frequency-modulated (FM) or amplitude-modulated (AM) subcarrier oscillators using frequency division, and pulse-width modulation (PWM) using time division. Evaluation of these methods is still in progress, but to date the AM frequency division method is preferred because with this system the electronic circuits which are required to be installed in the reactor vessel would be the simplest and therefore the most reliable.

The FM frequency division method, when compared with the AM system, will require an additional circuit stage to modulate the oscillator. The AM frequency division method will employ a fixed frequency oscillator with constant amplitude. Serial operation of a PWM multiplexer requires timing circuits that depend upon complete operation in order to function at all. Timing pulses operate counting flip-flop stages that sequentially couple signals into the transmission link. Loss of one of these stages can stop the coupling of signals beyond that point in the sequence.

It should be pointed out that developmental difficulties exist only because of the severe environment in which the multiplexing system must operate. Components must be chosen that will survive the high temperature and radiation extremes, approximately 700 F, 10^{19} nvt, and 10^{11} R. Ordinary solid-state components are immediately eliminated from consideration since their radiation tolerance is only about 10^{13} nvt. The tunnel diode was considered a possible exception; however, environmental

conditions are still in excess of predicted capability of these devices, their radiation tolerance being about 10^{14} nvt.

It is felt that the use of tunnel diodes beyond recommended operating conditions would only impair system reliability. Helping in this decision was the fact that metal-ceramic vacuum tubes are available which can be operated in reactor environments. A summary of the operating range of transistors, ceramic tubes, and thermionic integrated micro module (TIMM)* circuit elements is listed below:

1. Temperature

a. Transistor solid-state circuits

Continuous operating ambient temperature	60°C
--	------

Storage temperature	-65°C to 85°C
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b. Ceramic tube with high temperature circuit elements

Continuous operating ambient temperature	200°C to 300°C
--	----------------

Storage temperature	-100°C to 400°C
---------------------	-----------------

c. TIMM circuits

Continuous operating ambient temperature	580°C ± 20°C
--	--------------

Storage temperature	-100°C to 800°C
---------------------	-----------------

*Manufactured by the Receiving Tube Department of the General Electric Company at Owensboro, Kentucky.

2. Radiation (Neutron and Gamma)

- a. Transistor solid-state circuits 10^{12} to 10^{13} n/cm² and 10^8 R
- b. Ceramic tube with high temperature components 10^{13} n/cm² and 10^8 R
- c. Ceramic tube and TIMM circuit elements In excess of 3×10^{18} n/cm² and 10^9 R
- d. TIMM circuits In excess of 3×10^{18} n/cm² and 10^9 R

A number of TIMM circuit elements have been ordered to allow construction of an oscillator that can be operated in the reactor environment. Unpublished information on tests being conducted at the Battelle Reactor Facility (September 1962) under the Air Force, Contract AF 33(616)-8096, indicate that TIMM components are not damaged at 3×10^{18} n/cm². By extrapolating data available on the radiation resistance of the materials used, it is expected that operation of the TIMM circuits would be satisfactory after an exposure of 10^{21} n/cm²; however, supporting test data will not be available since the Battelle reactor tests will be terminated after 10^{19} n/cm² exposure.

TIMM circuitry will be developed around an AM frequency division telemetering system as indicated in the following schematic:

R_1 - Detector with neutron heated resistive element.

R_2 - Detector that monitors environment temperature.

—[]— - Isolation resistor.

Design Considerations

- a. $R_1 = R_2$ under conditions of no neutron radiation exposure.
- b. Change of I due to R_1 and R_2 changing is less than 1 per cent.

$\therefore E_m - (E_c - E_m) = \text{Differential temperature between } R_1 \text{ and } R_2.$

$2 E_m - E_c \approx \text{Heating of } R_1 \text{ from neutron radiation.}$

The system operation is described briefly as follows. An oscillator operated at fixed frequency and amplitude, is connected across the resistive element monitor, which is basically two resistors connected together

in series. Since one resistor is coated with uranium, its resistance - and the voltage drop across it - is a function of neutron flux. Approximately 100 to 200 of these signals distributed across the frequency spectrum (1 kc to 100 kc) may be added together on one output wire; the exact number will depend on band width limitations.

To obtain the high selectivity required, investigation of the availability of a phase-locked product detector has been undertaken. This detector is so designed that it will respond to the output of only one oscillator, thus performing like a very narrow band filter. Normal oscillator frequency drift is automatically followed by the phase error correction circuitry.

This system is capable of high information density and inherently reliable performance; therefore, major effort will continue to be directed toward this approach.

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SECTION V

CONCLUSIONS

As a result of investigations to date, in-vessel multiplexing can be accomplished in two ways: electromechanical commutation, or mixing of subcarrier oscillators. It seems well within the scope of this phase to continue investigations of both schemes. There are cases where one method would be preferred above the other.

For example, low level signals, such as thermocouple signals, will best be multiplexed by an electromechanical device since noise levels are usually less than 100 microvolts with such switches. Subcarrier modulation normally requires signals of the order of 1 volt or more, and noise levels are generally in the millivolt region. On the other hand, signals in the volts region can be attained with ion chambers and resistance elements, and it may be desirable to have the continuous monitoring features of the frequency division multiplex.

Of course, it is also common in telemetering systems to use a combination of the two schemes; that is, to commutate slowly varying signals for input to a subcarrier, while feeding critical or fast varying signals directly to other subcarrier stages. In this way, optimum use is made of the transmission link.

The multiplexing unit should be installed in the pressure vessel in such a way as to optimize reliability, access for service, and cable

routing. The vessel wall just below the head is such a location in a boiling water reactor. The unit would be out of the way of core maintenance, and yet be readily accessible when the head is removed. Cables could be routed down the vessel wall to the top of the core.

Since the unit is to be used for ion chambers, the use of a hermetically-sealed connector is dictated for electrical connections to detectors. If at all possible, detectors should be removable without disturbing the entire system.