PRESSURE AND TEMPERATURE INSTRUMENTATION
FOR DYNAMIC MEASUREMENTS
IN THE KEWB PROGRAM
A SUMMARY REPORT

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CONTRACT: AT(11-1)-GEN-8
ISSUED:

NOV 15 1960

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ACKNOWLEDGMENT

We wish to thank the members of the Physics Research Section of the Rocketdyne Division for their continued support and cooperation in this program, and in particular for the construction of the shock tube and development of the Dual DADEE.

We are particularly indebted to Dr. M. A. Greenfield for fruitful theoretical discussions.

Thanks are also due to Mr. Franklin Curtis for very effective work in construction and testing of apparatus. We are grateful to Mr. William Nelson for help given in the earlier phases of the program.

I. INTRODUCTION

The KEWB (Kinetic Experiments on Water Boilers) reactor^{1,2} is a homogeneous solution-type reactor. The operation of this reactor is devoted to an experimental investigation of the safety of aqueous homogeneous reactors, and includes power transients resulting from reactor periods down to 2 milliseconds, and ramp reactivity inputs involving as much as 4% $\Delta k/k$. The reactor fuel consists of 11.5 liters of a solution which is 0.77M in uranyl sulphate (UO_2SO_4 >90% U^{235}) and 0.5M in sulphuric acid, resulting in a pH of about 0.3. Because of radiolytic decomposition of the water in this solution, hydrogen and oxygen are generated during operation of the reactor. In normal operation this gas mixture is diluted and swept over a platinized alumina catalyst bed, where it is recombined catalytically into water (see Figure 1). In a large power excursion, a considerable volume of stoichiometric hydrogen and oxygen, frequently as much as 15 liters, is suddenly generated, and ignition may occur because of the high concentration of flammable gas reaching the catalyst bed. During a fast transient, the temperature of the fuel solution also rises from room temperature to about 90°C in a few milliseconds. These transient phenomena present special instrumentation problems.

A short time after the KEWB began experimental operation, it was recognized that the pressure and temperature instrumentation then in use, although adequate for the majority of the intended measurements, would not suffice for all the measurements considered necessary to complete the investigations of the safety of aqueous homogeneous research reactors. The purpose of the KEWB Transient Instrumentation Development Project was to develop pressure and temperature measurement systems capable of detecting and recording these rapid phenomena. Unbonded strain wire pressure transducers manufactured by the Consolidated Electrodynamics Corporation were originally used, but were found to be not capable of withstanding hydrogen and oxygen explosions without damage, because of the attendant high accelerations. Explosion shock waves produced consistent failures from breaking of strain wires. In addition, the 20-kc carrier generator, amplifier, and recording galvanometer, which

Figure 1. Wet Type Gas Handling System Flow Diagram

comprised the rest of the system, were not able to reproduce accurately the sharp pressure peaks. (Under the explosion conditions expected to prevail, the pressure rise occurs in a small fraction of a microsecond.)

One suggestion to improve this situation was to measure the dynamic pressures with strain gauges attached to the core vessel. However, it was concluded that such a system would not be good for several reasons. Since the natural frequency of the core vessel would be low, the response time would be correspondingly slow. Calibration of the system would be difficult and the output would be small compared to that from pressure transducers.

The pressure transducers on the reactor vessel were held in flange-type mountings so that the diaphragms were flush with the inner surface of the vessel. The fuel solution came in direct contact with the diaphragms. An example of the corrosive action of the fuel solution is the effect on the diaphragms of the original pressure transducers in the KEWB. The cases of these transducers were fabricated from Type 416 stainless steel. Before installation, the sensing surfaces were gold-plated. However, the gold-plating did not prove impervious to the solution and severe pitting developed in the steel diaphragms. The corrosive action was caused primarily by the H_2SO_4 in the solution, while the UO_2SO_4 may have had an inhibiting influence.

The iron-constantan sheathed thermocouples used to measure the fuel solution temperature were made from mineral-insulated thermocouple wire. These thermocouples were too slow in response to follow the temperature rise in a 2-millisecond transient, since they had a time constant of about 20 milliseconds, while a time constant of less than 1 millisecond was required.

Maximum power excursions are induced in the core of the KEWB reactor by means of a pneumatically-operated fast reactivity device. This device removes a rod containing a neutron absorber from the central exposure tube of the reactor in approximately 20 milliseconds. The poison rod removal makes the reactor supercritical with the reactivity necessary to establish a 2-millisecond reactor period. The reactor power is observed to rise exponentially until it reaches approximately 10% of the peak value, at which point the effects

of the intrinsic control and shutdown mechanisms begin to appear. The inherent reactor shutdown process is the increased neutron leakage from the core which results from voids produced by radiolytic gas bubbles and from increasing fuel solution temperature. This process causes the power curve to fall rapidly after maximum power is attained. During such a transient, 4 megawatt-seconds of energy are released in the core in about 15 milliseconds and a peak power of over 500 Mw is reached.

During an excursion, the first pressure increase in the system is caused by the buildup of expansion pressure due to the rapid evolution of hydrogen and oxygen. This is a rather broad pressure pulse which is first seen at the bottom of the core. About 3.3 milliseconds after the maximum of this pressure wave occurs, a sharp pressure pulse is seen at the top of the core. This is the result of the fuel solution surface impinging upon the top transducer as fuel is expelled into the overflow chamber. These expansion pressures are much slower phenomena than the hydrogen-oxygen explosion pressures which may occur in the radiolytic gas whenever it exists in the system. Whereas the time at which expansion and impact pressures will occur can be predicted, hydrogen and oxygen explosions may occur at any time shortly after a power transient.

Two known sources of ignition of the hydrogen-oxygen mixtures are dried particles of UO_2SO_4 , which may be formed in or near the core, and the recombiner catalyst, whose temperature can increase to beyond the ignition temperature of about 500°C . The pressure resulting from these explosions can be as high as 20 times the initial pressure of stoichiometric hydrogen and oxygen without reflection, and approximately 40 times the initial pressure at a point of reflection of the shock front.^{3,4} A maximum pressure change during this type of an explosion occurs in a small fraction of a microsecond. Generally, upon ignition, the reaction in a hydrogen and oxygen mixture starts out as slow burning. After the flame front proceeds for some distance, enough energy is fed into it to cause it to accelerate into a detonation front. The magnitude of this distance depends upon the mixture, the pressure, the type of ignition, and the diameter and configuration of the containing vessel. The "run-up distance,"

or distance at which equilibrium detonation is reached, is on the order of ten times the diameter of the vessel. At equilibrium, a detonation shock wave in stoichiometric hydrogen and oxygen propagates with a velocity of 2830 meters per second and a maximum flame temperature of 3678°K.⁵

The objectives of the instrumentation development project were clearly defined. The pressure transducers had to have fast response times, in the microsecond range, be able to withstand many hydrogen-oxygen explosions without damage, resist corrosion by the core solution containing uranyl sulphate and sulphuric acid, operate satisfactorily in intense nuclear radiation fields of 10^{15} n/cm²-sec, and withstand temperatures up to 150°C. It was also required that the transducers be small in size in order to fit existing mounting apertures, and be capable of static readings and calibrations in order to allow periodic checks of the sensitivity after installation. The recording devices were also required to have fast response, in the microsecond range or better. For temperature sensors, time constants smaller than a millisecond were needed. Durability and resistance to corrosion and radiation for these devices were also necessary properties, in the same degree as for the pressure transducers.

II. TRANSDUCER INVESTIGATIONS

A. TYPES OF TRANSDUCERS

In order to expedite the development of a satisfactory pressure system, it was decided to purchase the more promising types of commercially available pressure transducers and test them for the qualities of interest, rather than to engage in a specialized design and fabrication effort. Little information was available on such subjects as radiation damage to transducers, radiation sensitivity, mechanical resistance to hydrogen-oxygen explosions, and dynamic response. A survey was made to obtain such information as was available pertaining to the application and the problems.

Eight different makes of transducers were selected for evaluation. These transducers were chosen with a pressure range of 0-1000 psi or higher because it was anticipated that hydrogen-oxygen explosion pressures in KEWB would fall in this range. Small size and flush-type mountings were preferred because in this way the most rapid response* can be achieved. Photographs of these transducers, from which the sizes can be judged, are shown in Figures 2 through 8. Figure 9 shows the internal structure of a small unbonded strain wire transducer produced by Statham Instruments, Inc.

A few preliminary tests were made on two variable-reluctance types, the Wiancko model P1402 and the Ultradyne model S-6B. Neither of these was a flush-mounting transducer, and their response time was found to be about 50μ sec, which was too slow for our application. While these are good for certain applications, it was not certain whether they would be available in corrosion-resistant materials and no further evaluation was made.

B. CONSTRUCTION AND APPLICATION OF SHOCK TUBE

The testing and evaluation program for the various types of transducers mentioned above required the design and construction of specialized apparatus. A remotely-controlled shock tube was built (Figure 10). This shock tube was about 8 ft long and was made in two sections. One, the high-pressure section,

* The response time is defined as the time required for the output signal to go from 0 to 90% of maximum.

Figure 2. Statham Transducer (right), Omega Transducer (left) and End Caps for Mounting Transducers on the Shock Tube

Manufacturer-Statham Instruments Inc.

Manufacturer-Omega Instrument Co.

Model - PA217-1M-350

Type - strain wire

Element - unbonded 4-arm bridge

Connector - 4 pin

Excitation - 7v dc or ac

Model - 21-10

Type - variable capacitance

Connector - subminax coaxial

Excitation - 25 Mc carrier

Figure 3 Dynisco Transducer

Manufacturer Dynamic Instrument Co

Model - P3A-1M

Type - strain wire

Element - unbonded 4-arm bridge

Connector - 5 pin

Excitation - 15v dc or ac

Figure 4. Norwood Transducer

Manufacturer - Norwood Controls Division of Detroit Controls

Model - EPK-1000

Type - strain wire

Element - bonded-2 arms of bridge

Connector - 3 pin

Excitation - 45v dc or ac

Figure 5. SLM Transducer

Manufacturer - Kistler Instrument Co

Model - PZ-14

Type - piezoelectric

Element - quartz

Connector - coaxial

Figure 6. Erich Brosa Transducer

Figure 7. Endevco Transducer

Manufacturer - Endevco Corporation

Model - 2501-1000

Type - piezoelectric

Element - ceramic

Connector - Microdot coaxial

Figure 8. Atlantic Research Transducer

Manufacturer - Atlantic Research Corp.

Model - LD-77

Type - piezoelectric

Element - lead zirconate

Connector - Microdot coaxial

Figure 9. Internal Strain Wire Support Structure of a Small Statham Transducer

Figure 10. Shock Tube with Control Circuit

was made of stainless steel and the other, the low-pressure section, was made of Type 6061 aluminum. The ID was 1 inch and the wall thickness was 1/4 inch. This gives a bursting pressure of about 10,000 psi. The aluminum section was designed so that it would fit into the central exposure facility of the KEWB and extend to the center of the core. The transducer, mounted on the end of the tube, would then be in the high-flux region during reactor operation. The 6061 aluminum was chosen because it was desired to minimize the induced radio-activity. The overall length of the shock tube was limited by the small size of the reactor room. Only six feet of space were available between the north face of the reactor and the north wall of the room. Pressure transducers were exposed to shock waves at the center of the reactor simultaneously with exposure to intense neutron and gamma radiation. The shock waves were generated by bursting mylar diaphragms by means of a knife driven by an electromagnet (Figure 11). Changing of diaphragms while the shock tube was in the reactor room was done automatically by remote control (see Figure 12). Clamping and unclamping of the diaphragm was accomplished by a pneumatic cylinder at the rear end of the shock tube. In the laboratory, the same shock tube was used without diaphragms for producing hydrogen and oxygen detonation shock waves. The burst pressure of the shock tube was sufficient to handle explosions in $2\text{H}_2 + \text{O}_2$ with 250 psi initial pressure. A spark plug was provided near the back end of the shock tube to ignite the hydrogen and oxygen mixture. The shock tube was used initially to test the various transducers for the following characteristics: response time, natural frequency, wave form of the ringing, and ability to withstand hydrogen and oxygen explosions without damage.

The transducer under test was mounted at the end of the shock tube where the shock wave is reflected. In this position, the greatest possible pressure step for a given initial pressure is obtained. The output of the transducer (and amplifier, if one were necessary) was observed with a Tektronix model 535 oscilloscope and a Polaroid camera. The oscilloscope could be triggered either internally on the initial rise of the signal or externally from the signal given by an SLM transducer located near the center of the shock tube. The SLM transducer was chosen for triggering because it was durable, simple to use, and mountable in a spark-plug boss.

Figure 11. Electromagnetically Driven Knife

Figure 12. Shock Tube Diaphragm Changing Device

The Rocketdyne Division of North American Aviation, Inc., had under development, at this time, an electronic circuit to compensate for ringing and time lag in the response of transducers. This circuit was known as the Dynamic Analog Differential Equation Equalizer (DADEE).⁶ It solved electronically the equation of motion of a transducer with one degree of freedom, $\alpha \ddot{x} + \beta \dot{x} + x = F(t)/k$, for the forcing function $F(t)$, once the inertia constant α and the damping constant β were known. In this equation, k is the elastic constant of the system and x is the displacement. The DADEE produced a definite improvement in the output signal for the Omega Instrument transducer, the Dynisco transducer, the SLM, the Norwood, and the Statham. The DADEE removed some of the ringing and shortened the response time to less than 5 microseconds for all transducers whose ringing is listed as "clean" in Table I (see also Section II-H). For the other transducers, where many frequencies were present, the DADEE complicated the situation because it amplifies frequencies above that to which it is tuned. In the case of those transducers where the DADEE did help, there was still present a higher frequency amplified to a considerable amplitude, which prevented direct interpretation of the pressure trace. Further development of the DADEE was undertaken to overcome this difficulty. This led to the development of the Dual DADEE.⁷ The Dual DADEE electronically solves the differential equation $A_1 \ddot{X}_1 + A_2 \ddot{X}_2 + B_1 \dot{X}_1 + B_2 \dot{X}_2 + X_1 + X_2 = DF(t)$, where D is a proportionality constant. The signal X enters the Dual DADEE where two similar sets of operations are performed on it. One set of operations consists of differentiating X twice with respect to one of the system's resonant frequencies, forming $A_1 \ddot{X}_1$ and $B_1 \dot{X}_1$. Similarly, differentiating twice with respect to the system's second frequency forms $A_2 \ddot{X}_2$ and $B_2 \dot{X}_2$. These four quantities are mixed with the original signal by adding circuits to form the left side of the above equation. The inertia constants A_1 and A_2 and the damping constants B_1 and B_2 are introduced by potentiometers. They are determined experimentally by introducing the known ringing frequencies as described below. In operation, the Dual DADEE is first operated as a single DADEE and channel A is tuned to the known lowest ringing frequency of the transducer. The transducer is then excited by a shock wave and the output of the DADEE is recorded with an oscilloscope camera.

TABLE I
TRANSDUCER CHARACTERISTICS

Manufacturer	Atlantic Research	Atlantic Research	Dynisco	Endevco	Erich Brosa	Norwood	SLM (Kistler)	Statham	Statham	Omega
Model Number	LD-80	LD-77	P3A1M	2501-1000	6014	EPK-1000	PZ-14	PA-217TCa-1M-350	PA-217a-1M-350	21-10
Type	Lead Zirconate Piezoelectric	Lead Zirconate Piezoelectric	Unbonded Strain Wire	Piezoelectric Ceramic	Quartz Piezoelectric	Bonded Strain Wire	Quartz Piezoelectric	Unbonded Strain Wire	Unbonded Strain Wire	Variable Capacitance
Natural Frequency	~1000 kc	~1000 kc	18 kc	100 kc	95 kc	44 kc	43 kc	27 kc	32 kc	80 kc
Response Time in Microseconds	0.5	0.5	8	2	4	8	4	10	10	3
Sensitivity (Approx) [†]	3 mv/psi	0.01 v/psi	45 μ v/psi	25 mv/psi	2 mv/psi	40 μ v/psi	2.9 mv/psi	38 μ v/psi	25 μ v/psi	2.1 mv/psi
N ₂ Dynamic Sensitivity [§]	1.07 mv/psi	No test	69 μ v/psi	0.97 mv/psi	2.55 mv/psi	62 μ v/psi	3.73 mv/psi	44 μ v/psi	No test	2.9 mv/psi
2H ₂ + O ₂ Dynamic Sensitivity [§]	2.71 mv/psi	No test	71 μ v/psi	1.63 mv/psi	2.64 mv/psi	57 μ v/psi	4.45 mv/psi	42 μ v/psi	No test	1.9 mv/psi
Radiation Insensitive (yes - no)	No	No	Yes (with carrier)	No	No	No	No	Yes (with carrier)	No test	No
Cumulative Radiation Effects	10 ¹⁶ n/cm ²	20-25% loss of output	No test	None	~10% loss of first peak	<10% loss of output	No test	None	No test	10% loss of output
	10 ¹⁷ n/cm ²	Failed	No test	None	No additional change	None	No test	None	No test	50% loss of output
	10 ¹⁸ n/cm ²	No test	90% loss of output	93% loss of output	No test	No test	None	No test	Failed electrically	No test
Explosion Resistant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Effects	100°C	No test (see LD-77)	5% loss of output	None	15% loss of output	None	5% loss of output	None	10% loss of output	20% loss of output
	150°C	No test (see LD-77)	40% loss of output	5% loss of output	No test possible	No test possible	5% loss of output	None	10% loss of output	50% loss of output
Corrosion Resistant in UO ₂ SO ₄ + H ₂ SO ₄	Not available	Not available	Yes	Not available	Not available	Not available	Not available	Yes	No	Not available
"Clean" Ringing (yes - no)	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Calibration Means (yes - no)	(a) Static	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
	(b) Dynamic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Remarks		Superseded by LD-80		Maximum rated temperature is 110°C. Cable shorted before 150°C was reached	Cable fused at 130°C	Nitrogen cooled during temperature tests		Temperature compensated	First model	Has 25 mc carrier, saturation effects above 300 psi

* Static calibration curve

† Sensitivities may vary a great deal depending upon applied voltage for strain wire types and cable capacitance for piezoelectric types.

§ Dynamic calibration curves.

The higher ringing frequency will be apparent and can be measured. An oscillator set at each known ringing frequency is used to re-tune the two channels of the Dual DADEE to the transducer frequencies by setting the inertia and damping controls for minimum output (see Figures 13 through 15).

The hydrogen and oxygen for explosion tests were mixed in stoichiometric proportions in an underground tank of about 160 liters capacity. A diagram of the hydrogen and oxygen system is shown in Figure 16. The shock tube was evacuated before each test and then the gas mixture was introduced into the shock tube to the desired pressure, measured with the Ashcroft gauge.

An oscilloscope trace for a 1-atmosphere stoichiometric hydrogen-oxygen explosion taken with a Statham model PA217TCa-1M-350 transducer is shown in Figure 17. This trace is an excellent example of "clean" ringing because of the absence of multiple frequencies. The sweep is 100 microseconds per cm, represented by one large division. The small oscillation just before the shock front impact is caused by vibration traveling through the metal wall of the shock tube. The sweep was triggered by a signal from an SLM transducer 121 cm upstream. The time for a stable detonation to travel 121 cm should be 430 microseconds for the stoichiometric hydrogen-oxygen mixture. The time interval shown by Figure 17 is 420 microseconds. This a good check that the gas mixture is in the correct proportion. Using the method of Mosier and Luker,⁸ a curve (Figure 18) was plotted from this trace of signal voltage vs time, using the static sensitivity of the transducer to determine the pressures. Points were obtained by taking the average of a maximum and the preceding minimum on the voltage trace. Extrapolation of the curve to zero time gives a peak pressure of about 500 psig. Theoretically, using 40 as the factor of pressure rise in the shock wave in a $2\text{H}_2 + \text{O}_2$ detonation at a point of reflection, a pressure of 560 psi would be expected.^{3,4} Error in extrapolation and experimental error in the points are enough to account for the discrepancy.

The first exposure of transducers to radiation to determine prompt effects was done at a 50-kw power level, which gave a flux of $5 \times 10^{11} \text{ n/cm}^2\text{-sec}$ with the shock tube installed in the central through tube of the KEWB reactor. No effect was found at this flux level. Later tests made during slow transients

Figure 13. Dual DADEE - Front View

Figure 14. Dual DADEE - Top View, Channel A

Figure 15. Dual DADEE - Top View, Channel B

Figure 16. Hydrogen and Oxygen Handling and Storage System

Figure 17. Oscilloscope Trace of $2 \text{H}_2 + \text{O}_2$ Explosion in Shock Tube with Statham Transducer; Sweep is $100 \mu\text{sec/cm}$

Figure 18. Pressure vs Time in $2\text{H}_2 + \text{O}_2$ Explosion in Shock Tube with Statham Transducer

with powers of several hundred kilowatts also showed no effect. It became difficult to fire the shock tube at the proper time (within about 0.2 sec of peak power) using a manual button and a pneumatically-driven knife to puncture the diaphragm. An electromagnetically-driven knife and a thyatron circuit to be triggered from a log N power channel were designed and built. This system permitted control of the time of bursting of the diaphragm to within ± 2 milliseconds, so that the shock front could be made to reach the transducer very close to the time of peak power, even in a fast transient. With this system, eight different transducers, an Atlantic Research, a Dynisco, an Endevco, a Brosa, a Norwood, an SLM, a Satham, and an Omega, were exposed to 550-Mw peak power transients at the center of the KEWB and the outputs were observed. All eight displayed large radiation-induced signals. The Atlantic Research, the SLM, the Satham, and the Omega gave signals which would correspond to negative pressures of about 300 psi. The Dynisco and the Endevco gave radiation signals corresponding to positive pressures of 300 psi and 500 psi respectively. To obtain more information about the source and nature of these radiation signals, the experiment with the Satham transducer was repeated with the signal leads reversed at the transducer. The polarity of the true pressure signals reversed but that of the radiation signal remained the same. The magnitude was also the same. These facts indicated that the radiation signal came primarily from the lead wires rather than from the transducer. A brief investigation of radiation effects on wires and cables was then undertaken; these will be described in a later section. The Satham transducer was then utilized with a 20-kc carrier system. The radiation-induced signals were largely eliminated from the output because they were d-c signals to which the carrier amplifier did not respond. A residual radiation effect equivalent to about 25 psi at peak reactor power remained on the 0-1000 psi transducer.

C. SHOCK WAVE THEORY

Detonations in gas mixtures, such as the hydrogen-oxygen explosions considered in this report, involve chemical reaction processes which take place across sharply defined fronts. These reaction processes are very similar to shocks, which are discontinuities of pressure, velocity, density, and temperature

in a gas, except that energy (of formation) is liberated as the unburnt gas is converted to the burnt gas. The relations governing the transition from unburnt to burnt gas are derived from the laws of conservation of mass, momentum, and energy in the same way as the relations governing a shock transition.

Symbols are defined as follows:⁹

ρ_o = density in the unburnt gas

v_o = velocity of the unburnt gas relative to the reaction front

τ_o = specific volume of unburnt gas = $\frac{1}{\rho_o}$

p_o = pressure of unburnt gas

$E^{(o)}$ = complete energy for the unburnt gas

$I^{(o)}$ = complete enthalpy of unburnt gas

ρ_1 = density of the burnt gas

v_1 = velocity of the burnt gas relative to the reaction front

τ_1 = specific volume of burnt gas = $\frac{1}{\rho_1}$

p_1 = pressure of burnt gas

$E^{(1)}$ = complete energy for the burnt gas

$I^{(1)}$ = complete enthalpy of the burnt gas

m = mass flux.

By the law of conservation of mass,

$$\rho_o v_o = \rho_1 v_1 = m.$$

By the law of conservation of momentum,

$$p_o + \rho_o v_o^2 = p_1 + \rho_1 v_1^2 = P.$$

By the law of conservation of energy,

$$E^{(o)}(\tau_o, p_o) + p_o \tau_o + \frac{1}{2} v_o^2 = E^{(1)}(\tau_1, p_1) + p_1 \tau_1 + \frac{1}{2} v_1^2$$

From these three laws, the Hugoniot relation can be derived. This relation is

$$E^{(1)}(\tau_1, p_1) - E^{(o)}(\tau_o, p_o) = -\frac{1}{2}(\tau_1 - \tau_o)(p_1 + p_o)$$

Expressed in terms of enthalpy, this equation is

$$I^{(1)} - I^{(o)} = \frac{1}{2}(\tau_1 + \tau_o)(p_1 - p_o)$$

Knowing the enthalpy change, $I^{(1)} - I^{(o)}$, and the specific volumes τ_1 and τ_o , the pressure rise $(p_1 - p_o)$ in the detonation shock front can be calculated.

The detailed derivation is given in Appendix I.

Calculation of Pressure Steps

The pressure steps generated in the shock tube by bursting a mylar diaphragm holding nitrogen under pressure are calculated by the equation given by Wolfe.¹⁰ The pressure step is calculated for a point of reflection which represents the case for transducers mounted in the test position at the end of the shock tube. Thus,

$$P_5 = \frac{P_1(8 - \xi)}{(6\xi + 1)\xi},$$

where

P_5 = pressure in the reflected shock,

P_1 = initial pressure on the low side of the diaphragm,

and

ξ = shock strength.

For example, let us calculate the pressure step for the case where $P_1 = 14$ psia and $P_4 = 264$ psia, where P_4 is the pressure on the high side of the 5-mil diaphragm, so that $P_4 - P_1 = 250$ psi. Then

$$\frac{P_1}{P_4} = \frac{14}{264} = 0.0531.$$

From the curve on page 7 of reference 10, if $\frac{P_1}{P_4} = 0.0531$ and $\xi = 0.27$, we have

$$P_5 = P_1 \frac{(8 - 0.27)}{(6 \times 0.27 + 1) 0.27} ,$$

or

$$\frac{P_5}{P_1} = \frac{7.73}{2.62 \times 0.27} = 10.8 ,$$

from which

$$P_5 = 10.8 \times 14 = 152 \text{ psi},$$

$$P_5 - P_1 = 152 - 14 = 138 \text{ psi}.$$

$(P_5 - P_1)$ is the reflected pressure step. Frequently-used pressure steps are given below:

High Side (psig)	Low Side (psig)	Reflected Pressure Step (psi)
376	126	204
486	111	295
250	0	138
150	0	90

D. CORE MOCKUP TESTS

A mockup of the KEWB core vessel which was used for some of the hydrogen and oxygen explosion tests is shown in Figures 19 and 20.

In Figure 20, two ports (numbered 7 and 11) in which pressure transducers were mounted can be seen. A spark plug at the top of the mockup was used to

Figure 19. Core Mockup

Figure 20. Core Mockup (Close-up)

ignite the hydrogen and oxygen mixture. Observations of hydrogen-oxygen explosions were made with the SLM, the Endevco, and the Atlantic Research piezoelectric transducers. The spherical part of the mockup was filled with water to a level just above the lower port, No. 11, in the figure, and pressure observations were made both above and below the water surface. Results were not as reproducible as in the case of hydrogen-oxygen explosions in the shock tube. This is believed to result from the complex geometry of the test vessel, which strongly affects the establishment and maintenance of a detonation wave. In general, a transducer under the surface of the water displayed less ringing, considerably lower peak pressure (by a factor of 2-3), and a slower pressure rise than in the gaseous phase, requiring 50-100 μ sec to reach a maximum.

In some cases, a much higher pressure was seen at the transducer in No. 11 port than one would expect. In these cases, the pressure traces frequently showed a slow rise in static pressure before the shock wave arrived. This phenomenon, which has been termed "precompression," occurs in the core mockup because the "run-up distance" after ignition is insufficient, i. e., only about 7 times the diameter of the standpipe above the sphere. The effect is shown in Figure 21, which is a reproduction of a pressure trace of a hydrogen-oxygen explosion taken with a Dynisco transducer in No. 11 port of the core mockup. The effect is treated elsewhere," but this is briefly what occurs: An equilibrium detonation is not established immediately on ignition because the reaction starts out as slow burning. This burning heats some of the gas, which sends a compression wave into the rest of the gas with the speed of sound. If, then, the reaction becomes a detonation, it proceeds into the precompressed gas and produces locally an abnormally large pressure. This type of effect was also observed in the shock tube at a pressure of about 0.5 atmosphere absolute. It was manifested by an abnormally high pressure in the detonation at the end of the shock tube. At other initial pressures, the detonation reached the end of the shock tube either before, or (as in Figure 21) after the compression, so that there was no observed effect. Conditions in the shock tube were uniform and carefully controlled so that non-equilibrium effects were more reproducible than in the core mockup.

TIME $\rightarrow 200 \mu \text{ sec/cm}$

Figure 21. Hydrogen-Oxygen Explosion Pressure in Core Mockup Showing "Precompression"; Sweep is $200 \mu \text{ sec}$ per Large Division

E. CORROSION TESTS

The 0.5 molar sulphuric acid -0.77 molar uranyl sulfate core solution is very corrosive to many materials. Noble metals and Types 316, 321, and 347 stainless steel were known to withstand corrosion by this solution. 400 series stainless steels commonly used in transducer fabrication are not corrosion resistant in the core solution. Other materials which possibly would be exposed to this solution, such as the plastics used in some pressure transducer applications for coverings and sealants, and some stainless steel samples, were tested to determine corrosion effects of the solution. The results of tests on various plastics and glasses (used in thermocouple fabrication) and Type 304 stainless steel tubing are given in Table II. These results indicate that the epoxy plastics show the least effect and could be used in contact with KEWB fuel solution. It is noted that the Corning Types 0080 and 9010 glass used in fabricating thermocouples were unaffected. Tests on Ceramicite C-200 glass and Corning solder glass No. 7570 revealed that they disintegrated quickly in the solution.

F. RADIATION DAMAGE

An estimate of the integrated neutron flux to which a pressure transducer on the KEWB core would be exposed in a 3-month period gave a dose of approximately 5×10^{15} neutrons per cm^2 . On this basis, a series of irradiations was planned in order to investigate radiation damage to transducers made by all the manufacturers listed in Table I. Integrated fluxes for these irradiations will vary from a lower value of 10^{16} to a maximum of 10^{18} neutrons per cm^2 , in order to provide data of widest applicability. After an irradiation to 10^{18} nvt, the induced activity is quite intense and a minimum decay time of six months is needed before the active transducers can be conveniently retested. Because of the required six-month waiting period, the 10^{18} nvt irradiation was given at the beginning of the program rather than near the end. Tests at lower integrated fluxes were not necessary for those transducers which were unaffected by 10^{18} nvt. The Omega, the Erich Brosa, and the Norwood transducers were not received in time for this irradiation, which was carried out at the MTR. Each transducer was calibrated on the shock tube for dynamic sensitivity before and after the irradiation. The SLM model PZ-14 and the Dynisco model P3A1M were both unaffected by a dose of 10^{18} neutrons per cm^2 . These were

TABLE II
CORROSION TESTS

Material Designation	Original Weight (gm)	Length of Test	Result
Taylor LE-78 Phenolic-Cotton Fabric	1 9120	9 months	0 1929 gm loss of weight
Taylor XP-240 Phenolic-Paper Filler	1 8535	9 months	0 6006 gm loss of weight
Taylor C 296-Phenolic-Cotton Fabric	2 2929	9 months	0 1910 gm loss of weight
Taylor GEC-318 Epoxy-Glass Fabric	2 2783	9 months	0 7769 gm gain of weight
Taylor CE-328 Phenolic-Cotton Fabric	1 9337	9 months	0 3914 gm loss of weight
Taylor XXX-316 Phenolic-Paper Base	1 9055	9 months	0 3513 gm loss of weight
Taylor GSG-997 Silicone Resin	0 7567	9 months	0 1881 gm loss of weight
Taylor NS-6129 Phenolic-Nylon Fabric	1 7710	9 months	0 3867 gm loss of weight
Taylor G-5-324 Melamine-Glass Fabric	3 9669	9 days	Disintegrated
Epoxy Resin Type 1	2 4351	11 months	0 1589 gm gain of weight
Epoxy Resin Type 2	1 4883	11 months	0 1681 gm gain of weight
Epoxy Resin Type 3	1 9385	11 months	0 4665 gm gain of weight
Epoxy Resin Type 4	2 2766	11 months	0 8907 gm gain of weight
Epoxy Resin Type 5	2 3348	11 months	0 0698 gm gain of weight
Epoxy Resin Type 6	2 4096	10 months	0 1028 gm gain of weight
Epoxy Resin Type 7	2 2802	10 months	0 4097 gm loss of weight
Epoxy Resin Type 8	2 4676	10 months	0 3256 gm loss of weight
Epoxy Resin Type 9	2 3963	10 months	0 1087 gm gain of weight
Araldite Epoxy Resin with Thiokol Polysulphide Modifier and Calcium Carbonate	0 9522	19 days	Sample turned pink and small pieces broke off
Minnesota Mining Epoxy Polyamide	0 4205	~ 1 year	No change (room temperature)
Dow Corning RTV Silastic	1 6272	~ 1 year	Gave off gas
Type 304 Oxidized Stainless Steel Tubing	1 3991	10 days	Dissolved
Type 304 Unoxidized Stainless Steel Tubing	1 0743	6 months	0 0199 gm loss of weight
Corning 9010 Glass	0 8723	4 months	No change
Corning 0080 Glass	0 9913	4 months	No change

omitted from further integrated irradiations. The others in this test either were severely damaged, as indicated by a 90% or greater loss of output, or else they became completely inoperative. The other six transducers were irradiated in the ORNL graphite reactor to 10^{16} neutrons per cm^2 and, after recalibration, to 10^{17} neutrons per cm^2 . The complete results are given in Table I. There was little effect on any of the transducers at 10^{16} nvt except for the Atlantic Research model LD-80, which lost 20-25% of its output. At 10^{17} nvt, the Atlantic Research model LD-80 failed. The epoxy resin sensing surface had completely separated from the transducer. The Omega Instrument transducer suffered a large loss of output and displayed saturation effects at low pressures. The Endevco, the Erich Brosa, the Norwood, and the Statham suffered little or no damage at 10^{17} nvt.

An irradiation to 10^{17} nvt was made at ORNL for 19 plastic samples, 16 being epoxy resin to stainless-steel bonds. Each of these consisted of two fine wires sealed into a 1/8-inch hole in a stainless-steel disc with the epoxy resin. Of the 16, only two failed to pass the post-irradiation leak test, which consisted of testing for small leaks while the discs were subjected to 250 psi of static pressure. The results are given in Table III. The most noticeable effect was darkening of the plastic and development in some cases of a green or yellow coloration. Weight changes were negligible.

G. CABLE TESTS IN KEWB

In the experiments on prompt radiation effects on transducers described in section II-B, it was shown that the signals produced by radiation originated in a large part in the connecting signal cables. To investigate this point further, a series of tests on several types of cables was made in the central exposure facility of the KEWB reactor.

The method used to detect the radiation-induced voltages was to make a direct observation of the voltage output of the cables being tested, using a Tektronix oscilloscope. In all but one case, the end of the cable, placed either at the center of the exposure facility or near the reactor, was left open electrically. The oscilloscope was triggered externally by the output of a

TABLE III
RESULTS OF IRRADIATION OF PLASTIC SAMPLES

Sample Type and Number	Weight (grams)		Change (mg)	Leak Test	Color	
	Before	After			Before	After
1 Epoxy Polyamide Minnesota Mining Co.	0.1920	0.1923	+0.3	-	Red	Unchanged
2 Hysol H-1	2.1858	2.1871	+1.3	OK	Transparent	Greenish
H-2	2.0255	2.0263	+0.8	OK	-	-
3 Epoxy Plastics						
No. 1 formula 6-A	1.9923	1.9927	+0.4	OK	Clear Amber	Green Darkening
6-B	1.9559	1.9539	-2.0	OK	-	-
4 Epoxy Plastics						
No. 2 formula 6-1	1.8545	1.8548	+0.3	OK	Very Dark Brown	Darkened
1-2	1.9290	1.9294	+0.4	OK	-	-
5 Epoxy Plastics						
No. 3 formula 6W	1.8874	1.8878	+0.4	Leak	Clear Amber	Darkened
1Y	1.9152	1.9125	-2.7	OK	-	Dark Green
6 Epoxy Plastics						
No. 4 formula 1E	1.9464	1.9467	+0.3	OK	Clear Reddish	Darkened
6E	1.7773	1.7744	-2.9	OK	Brown	-
7 Taylor Fibre NS6129	1.2488	1.2442	-4.6	-	Amber	Darkened Reddish
8 Epoxy Plastics						
No. 5 formula 6M	1.7980	1.7982	+0.2	OK	Clear	Darkened
1M	1.9481	1.9409	-7.7	OK	Medium Brown	-
9 Epoxy Plastics						
No. 7 formula 1Q	2.0323	2.0270	-5.3	OK	Opaque	Unchanged
6Q	1.8754	1.8766	+1.2	Leak	Brownish Yellow	-
10 Epoxy Plastics						
No. 9 formula 1-L	2.0040	2.0019	-2.1	OK	Clear Greenish	Slight Darkening,
6-J	1.8936	1.8850	-8.6	OK	Brown	Yellow
11 Taylor Fibre GE318	1.6302	1.5066	-23.6	-	Light Grey	Darkened Greenish

thyatron which was fired from a logarithmic power channel during the rising portion of a KEWB power transient. To check that no spurious voltages were being picked up from the thyatron or elsewhere by the cables, the thyatron was also fired manually by applying an independent triggering signal. A portion of the thyatron signal was supplied to a galvanometer in the oscillograph, which was to make a routine record of reactor power, in order to determine at what time during the power transient the oscilloscope was triggered.

Radiation-induced signals were detected in the following types of cables: Microdot (Type 50-3804 used with Endevco and Atlantic Research transducers), MgO-insulated McGraw-Edison (for high-temperature service), MgO-insulated dual thermocouple leads, RG-62/U, RG-8/U, RG-19/U, and Twinax (Belden 8227). Ordinary 22-gauge stranded hook-up wire was also found susceptible to radiation. These signals, with the exception of those in the RG-19/U, were on the order of a few tenths to a few volts peak across one megohm (the oscilloscope resistance) during transients involving maximum fluxes of 5×10^{15} n/cm²-sec. Accompanying γ -ray fluxes were approximately 3×10^{16} γ /cm²-sec assuming an average γ -ray energy of 1 Mev, or about 5×10^{10} r/hr. The results of the cable tests are tabulated in Table IV.

In some cases, the signals followed the reactor power curve closely, as shown in Figure 22; in others such as Twinax, they appeared to be the sum of two opposing effects (see Figure 23). In the hook-up wire tests (Figure 22) an 800-ohm Shallcross wire-wound resistor joined the ends of the wires at the center of the exposure facility. In this test, the maximum radiation-induced signal was 22.5 mv. For the experiment with RG-19/U cable, a 5-foot section was inserted into the center of the exposure facility. This section was heavy cable with a 1/4-inch solid copper center conductor and 0.33-inch polyethylene insulation. The shield was copper braid, and the end of the center conductor was covered with polyethylene. In this test, the maximum radiation-induced signal at the peak of the radiation was +60 volts. This signal, which followed the reactor power curve closely, was the largest radiation-induced voltage observed. A -90v bias on this cable produced a relatively small effect (see Table IV).

TABLE IV

RADIATION EFFECTS EXPERIMENTS ON CABLES IN KEWB

Cable Description	Reactor Peak Power (Mw)	Bias	Radiation Signal (max)
RG 19/U	360	None	+ 60 v
RG 19/U	362	- 90 v	+ 53 v
RG 19/U	363	None	+ 8.0 v *
TWINAX: Cu wire	362	None	- 1.3, + 0.3 v
Tinned Wire	362	None	- 1.3, + 0.1 v
Hook-up Wire	365	None	+ 3.6 v
Hook-up Wire	432	None	+ 22.5 mv †
Bare Cu Wires	525	None	+ 1.3v §
Bare Cu Wires	560	+ 9.1 v	+ 10.2 v
Bare Cu Wires	532	- 9.1 v	- 7.2 v
Microdot 50-3804	525	None	+ 1.3 v
Microdot 50-3804	560	+ 9.1 v	+ 4.6 v
Microdot 50-3804	532	- 9.1 v	- 2.9 v
Microdot 50-3804	513	None	+ 1.5 v
McGraw-Edison	525	None	+ 0.6 v
McGraw-Edison	532	None	+ 0.65 v
McGraw-Edison	513	+ 9.1 v	+ 7.7 v
RG 62/U	596	None	+ 4 v

* Across 91×10^3 ohm resistance.

† With 800 ohm wire-wound resistance on end.

§ Presence of grounded aluminum liner in central exposure facility gave this effect.

Figure 22. Plot (Normalized) of Cable Radiation Signal and Reactor Power vs Time

Figure 23. Radiation Signal from Twinax Cable, 0.5 v/cm, 5 ms/cm from Left to Right. Each Trace is the Voltage to Ground Induced in One of the Two Center Wires of the Twinax

Another experiment was with an air-insulated rod, 1/4-inch in diameter, enclosed in a 3/4-inch-diameter concentric cylindrical tube. With a copper rod and an aluminum cylinder, a +1.6 volt signal was obtained. With the materials interchanged, a -1.2 volt signal was obtained. The signal vs time functions differed from each other as well as from the power curve, and showed little relation to the true power function.

In a test for loss of insulation resistance, a 9-volt bias was applied to one wire of a bare copper pair. Normal insulation resistance was 10^{11} to 10^{12} ohms. During the peak of a transient, the full 9 volts were seen at the oscilloscope input, which has a resistance of one megohm, indicating a comparatively low leakage resistance between the wires. A voltage is observed with no bias because of the grounded aluminum central tube liner, which gives a situation analogous to the copper rod and aluminum cylinder above. A similar test indicated a leakage resistance of 1.8 megohm for the Microdot cable and 0.28 megohm for the McGraw-Edison cable. A portion of this could occur across the air gap at the end of the cable.

Attempts have been made to explain the transient conductivity of insulators on the basis of carriers (electrons) produced by gamma rays in the insulator.¹² In the case of an insulator such as polyethylene, recoil protons, which also may act as charge carriers, are produced by fast neutrons. Photoelectric ejection of electrons from metals by ionizing radiation has been reported to result in sizeable currents of electrons and small photovoltages.¹² In general, however, no theory yet advanced explains satisfactorily the peculiar electrical behavior of insulators under irradiation, and accurate quantitative calculations are not yet possible.

H. EVALUATION OF TRANSDUCERS

On the basis of the characteristics of the pressure transducers listed in Table I, an evaluation was made with respect to the requirements of the KEWB experiments. Table I gives data on natural frequency, response time, sensitivity, radiation effects, temperature effects, corrosion, ringing, and calibration for the eight makes of transducers which were investigated. The piezo-electric types have the fastest response, which is desirable for observing

hydrogen-oxygen explosions, but they were lacking in other respects. For example, static calibration was impossible for the Atlantic Research and the Endevco piezoelectric transducers, and, although one could be obtained for the SLM and Erich Brosa transducers by using electrometer circuits, it would be inaccurate because of drift. The quartz piezoelectric transducers and the strain wire types were all undamaged by radiation dosages equivalent to more than a year of operation in the KEWB. All types listed were sufficiently explosion-resistant to withstand 50 or more explosions, although after about 50 hydrogen-oxygen explosions there were some failures of the unbonded strain wire types. The temperature-compensated strain wire transducers and the SLM quartz transducer had good temperature stability to 100°C. At the time when the ordering of explosion transducers for the KEWB became necessary, only the Statham or the Dynisco transducers were available in corrosion resistant 316, 321, or 347 stainless steel on a time schedule compatible with the KEWB schedule of experiments. Very recently, a new model of the Norwood bonded strain wire transducer with a welded diaphragm became available. It is likely that this also could be a corrosion-resistant design. An SLM transducer was used on the shock tube for oscilloscope triggering purposes. In this capacity, it withstood very many hydrogen-oxygen explosions without damage. In view of this as well as its other desirable characteristics, the SLM transducer, although not chosen for the present use, will be kept in mind for future applications in the reactor.

Table V presents an evaluation of the eight transducers investigated, on the basis of potential application under the restrictive conditions that are encountered in special reactor tests such as those conducted in the KEWB program. This evaluation applies only to that model of each transducer which was tested. Many other models for various special applications are available from the manufacturers. The limitations of the models tested are also set forth. This table should be an aid in the choice of transducers for this type of application.

Those transducers whose ringing is listed in Table I as "clean" are well compensated by use with the Dual DADEE. This means that the response time is shortened and the ringing is compensated so that an output curve (described

TABLE V
EVALUATION OF TRANSDUCERS

Transducer	Type	Potential Applications	Limitations
Atlantic Research	Piezoelectric	<ol style="list-style-type: none"> 1. Timing of shock waves 2. Smallest diameter of all transducers tested 	<ol style="list-style-type: none"> 1. Not suited for very high radiation fields 2. Limited to 100°C 3. Linearity is limited 4. No static readings
Dynisco	Unbonded strain wire	<ol style="list-style-type: none"> 1. Static and dynamic pressures 2. Large radiation doses 3. Use with carrier in radiation fields 4. Suitable for use with Dual DADEE 	<ol style="list-style-type: none"> 1. Temperature limited to 150°C 2. Response slower than piezoelectric types
Endevco	Piezoelectric	<ol style="list-style-type: none"> 1. Timing of shock waves 2. Peak explosion pressures 	<ol style="list-style-type: none"> 1. Limited to 110°C 2. No static readings
Erich Brosa	Quartz piezo-electric	<ol style="list-style-type: none"> 1. Dynamic pressures 	<ol style="list-style-type: none"> 1. Static readings limited by drift 2. 400 series stainless-steel case
Norwood	Bonded strain wire	<ol style="list-style-type: none"> 1. Static and dynamic pressures 2. Use with carrier in radiation fields 3. Suitable for use with Dual DADEE 	<ol style="list-style-type: none"> 1. Cooling required 2. Response slower than piezoelectric types
SLM	Quartz piezo-electric	<ol style="list-style-type: none"> 1. Dynamic pressures 2. Large radiation doses 3. Temperatures to 300°C 4. Suitable for use with Dual DADEE 	<ol style="list-style-type: none"> 1. Static readings limited by drift
Statham	Unbonded	<ol style="list-style-type: none"> 1. Static and dynamic pressures 2. Use with carrier in radiation fields 3. Use for corrosive medium 4. Suitable for use with Dual DADEE 	<ol style="list-style-type: none"> 1. Limited to 110°C 2. Sensitive to case distortion 3. Response slower than piezoelectric types
Omega	Variable capacitance	<ol style="list-style-type: none"> 1. Static and dynamic pressures 2. Suitable for use with Dual DADEE 	<ol style="list-style-type: none"> 1. Limited to < 100°C 2. Sensitive to radiation even with carrier 3. Saturation effects

by the function $R(t)$ given below) close to the true pressure curve, even for hydrogen-oxygen explosions, is obtained. Figure 24 shows the output of a Statham transducer for a hydrogen-oxygen explosion in the shock tube without the Dual DADEE, and Figure 25, with the Dual DADEE.

Figure 25 gives additional evidence that a correct pressure is obtained for a hydrogen-oxygen explosion by reading the first peak in the signal given by the Dual DADEE. This evidence is the fact that in Figure 25, 200μ sec after the shock front is recorded, the signal has fallen by a factor of e , as in Figure 18, indicating an exponential decay in pressure. In connection with any dynamic pressure-recording system, the question arises as to how well a recording instrument with time constant τ will follow a driving function which consists of a vertical rise and then an exponential decay with period T . This type of driving function is encountered in hydrogen-oxygen explosion pressures (Figure 18) and it may be assumed to be represented by the form $e^{-\frac{t}{T}}$ when normalized. Let the response of the pressure recording system be of the form

$$A(t) = 1 - e^{-\frac{t}{\tau}} .$$

It can be shown that the resultant normalized output is then

$$R(t) = \frac{T}{T - \tau} \left[e^{-\frac{t}{T}} - e^{-\frac{t}{\tau}} \right]$$

and the maximum output is

$$R_m = X \frac{X}{1-X} = e^{-\frac{t_m}{T}} ,$$

where $X = \frac{\tau}{T}$. For a hydrogen-oxygen explosion, T is taken as approximately 200μ sec. For the pressure system with the Dual DADEE, τ is taken as 3μ sec. Then

$$X = \frac{\tau}{T} = \frac{3}{200} = 0.015$$

Figure 24. Uncompensated Output of Statham Transducer for $2\text{H}_2 + \text{O}_2$ Explosion.
Sweep - $500 \mu\text{sec/cm}$

Figure 25. Output of Statham Transducer for $2\text{H}_2 + \text{O}_2$ Explosion Compensated by Dual DADEE. Sweep - $500 \mu \text{ sec/cm}^2$

and

$$R_m = (0.015)^{\frac{0.015}{1-0.015}} = (0.015)^{0.0152},$$

from which

$$R_m = 0.94.$$

Thus the system records about 94% of the peak pressure in the explosion.

A comparison in Table I of the static and dynamic sensitivities of each transducer (using the Dual DADEE where possible) reveals that the sensitivity of the Statham transducer by static and dynamic calibrations is more uniform than that of the others. A static, a nitrogen dynamic, and a hydrogen and oxygen explosion calibration curve for a Statham model PA217TC-1.5M-350, all taken with the shock tube, are shown in Figures 26, 27, and 28.

The Statham model PA217TC-1.5M-350 (1500 psi range) unbonded strain-wire transducer was chosen for transient pressure measurements in the KEWB for the following reasons: 1) its response (with the Dual DADEE) is sufficiently fast, with only 2 or 3 microseconds required for full response to pressure changes; 2) it can withstand hydrogen-oxygen explosions; 3) its ringing frequencies, namely 35 and 100 kc, are readily compensated by the Dual DADEE; 4) the transducer can be statically calibrated; 5) it is unaffected by a dose of 10^{17} neutrons/cm²; 6) it is small and mounts flush in the original mounting flanges on the core; and 7) it is available in Type 347 stainless steel so that it is not corroded by the fuel solution.

I. THE FINAL PRESSURE SYSTEM

The pressure instrumentation system chosen for installation on the KEWB reactor consists of four pressure channels, each with a Statham transducer, a Kintel dc amplifier, a Dual DADEE, and an oscilloscope channel for recording (see Figure 29). Three Tektronix oscilloscopes were utilized, and the oscilloscope traces were photographed with Polaroid cameras. The transducers were operated on 6 volts dc from batteries. They were ordered from Statham Instruments, Inc., to meet the required specifications as to case size and material, absence of organic insulators, natural frequency of ringing, ability

Figure 26. Static Calibration Curve for Satham Pressure Transducer

Figure 27. Nitrogen Dynamic Calibration Curve for Statham Pressure Transducer with Dual DADEE

Figure 28. Hydrogen-Oxygen Explosion Dynamic Calibration Curve for Statham Pressure Transducer with Dual DADEE

Figure 29 Block Diagram of One Channel of the Pressure System Installed in KEWB

to withstand hydrogen-oxygen explosions, pressure limits, zero unbalance, compensated temperature ranges, and linearity. These specifications are given in detail in Appendix II. A 0-1500 psia range was specified because it was felt that the extra range above that of the 0-1000 psia models described in Table I might be required. It was expected that this range would still have about the same ringing frequencies and would better withstand the pressure in hydrogen-oxygen explosions.

Each of the 1500-psia transducers received for use in the KEWB was calibrated statically, and also dynamically with shock waves in nitrogen and with stoichiometric hydrogen-oxygen explosions. These included explosions at initial gas pressures up to 2 atmospheres absolute, which leads to a step change of about 1100 psi at the transducer. A Dual DADEE circuit was used for the calibrations. Sensitivities were in the range 20.6 ± 3 microvolts/psi for all the transducers by all three methods.

The transducers are located at the top of the core, at the bottom of the core, on the overflow chamber, and on the recombiner. After initial installation, the system was pressurized to low pressures (less than 250 psig) to check the system operation. It was noticed that the transducers at the top and at the bottom of the core gave static pressure readings about 25% higher than before they were mounted on the core. The others gave about the same readings as before. When removed from the mounting flange, these two transducers produced the same signals as in the original calibration. The conclusion was that the mounting surfaces at the top and at the bottom of the core distorted the transducer case, producing the increase in static sensitivity. The stressed mounting was reproduced on the shock tube by using a washer with radial corrugations under the transducer. The dynamic sensitivity showed no significant change even though the static sensitivity had increased.

The pressure transducers mounted on the core responded to both radiation and vibration. To compensate for this effect, each transducer mounted on the core had another transducer mounted adjacent to the first transducer, but not communicating with the inside of the core vessel. The compensation is

accomplished by subtracting the signals by means of a differential preamplifier in the oscilloscope. Operating experience has shown that, in most cases, the radiation signals occur before the pressure signals in a fast transient, and these, as well as the signals caused by vibration of the spherical part of the core vessel, are compensated for fairly well by the compensating transducer.

Sweep times on the oscilloscopes as low as 2 milliseconds/cm have been required in order to observe the shapes of impact pressure pulses occurring after transients of periods down to 2 milliseconds. Triggering is accomplished with a thyratron circuit fired by the signal from a log N power channel. This pressure system gives a direct peak pressure readout and is capable of full response to pressure changes within 2 or 3 microseconds. Data are available for inspection immediately after the transient. A typical pair of pressure traces for the top and for the bottom of the core during a 2-millisecond transient is shown in Figure 30 for transient 295B.

When hydrogen-oxygen explosions are to be observed, a different mode of triggering is used because the time at which any explosion occurs is more or less random. One oscilloscope is triggered internally from the signal given by the transducer on the overflow chamber as the explosion wave passes that location. Figure 31 shows the pressure traces at 100 μ sec/cm obtained from the transducers on the overflow chamber and at the top of the core for a hydrogen-oxygen explosion after transient 36I. The peak which occurs first (upper trace) represents a pressure of 275 psi in the overflow chamber and the peak on the lower trace 190 μ sec later represents a pressure of 406 psi at the top of the core. The oscilloscope for the transducers at the top and at the bottom of the core is triggered simultaneously with the triggering of the oscilloscope for the overflow chamber. This oscilloscope operates on a slower sweep, since it takes several milliseconds for the detonation shock front to reach the bottom of the core through the solution. Figure 32 shows the oscilloscope pressure traces for the top of the core (upper trace) and the bottom of the core (lower trace) in a hydrogen-oxygen explosion occurring during transient 33I. The sweep is 500 μ sec/cm. The pressure step is detected at the top of the core a little more than 3 milliseconds before it is detected at the bottom of the core.

Figure 30. Pressure Traces for Top of Core (Upper) and Bottom of Core (Lower) in a 2 ms Transient. Sweep - 2 ms/cm. Peak Pressures:
Top of Core - 400 psi, Bottom of Core - 260 psi

Figure 31. Pressure Traces for Overflow Chamber and Top of Core in Hydrogen Oxygen Explosion after Transient 36I. Sweep is 100 μ sec/cm

Figure 32. Pressure Traces for Top of Core (Upper) and Bottom of Core (Lower) in a Hydrogen-Oxygen Explosion Occurring After Transient 33I.
Sweep is 500 μ sec/cm

In this case, the peak pressure is 280 psi at the top of the core and 240 psi at the bottom of the core. The pressure rise is much less sharp at the bottom of the core because here the transducer is under fuel solution, which attenuates the shock front. Generally, ignition occurs in the recombiner and the reaction travels into the overflow chamber and then into the core (see Figure 1). Ignition has been found to follow a power pulse only after a substantial time increment, usually ranging from 15 seconds to two minutes. Under these circumstances, the reactor atmosphere has the opportunity to reach an equilibrium pressure distribution. This allows the core vessel to be at the lowest system pressure possible at the time of ignition, and since the maximum pressure developed in the explosion is proportional to the initial pressure, the peak pressure in the vessel is minimized and tends to be more or less uniform regardless of the circumstances under which the transient is conducted. No significant dependence of the explosion pressure on coolant flow, temperature of the catalyst bed, or method of reactivity input has been detected. The maximum pressures have been measured as 470 psi in the spherical portion of the core vessel and 550 psi in the overflow chamber.

When very slow sweep rates of 1 sec/cm are used to observe reactor transients, an effect on the pressure transducers caused by their heating by the hot fuel solution is observed about a second after the transient has occurred. This effect corresponds to a maximum negative pressure of a few hundred psi and is slowly varying, changing a negligible amount in 20 milliseconds. Thus it produces no effect, or at most a small downward shift of the whole trace, on pressure traces as they are taken during transients, using fast sweep rates such as 2 milliseconds/cm. For hydrogen-oxygen explosions, still faster sweep times such as 100 microseconds/cm are used, so that only a downward shift of the whole trace, whose magnitude depends on the time when the explosion occurs, is the observed heating effect. Complete results of the explosion experiments are given in Reference 13.

All of the Statham transducers installed in the KEWB were subjected to a number of hydrogen-oxygen explosions in the laboratory before installation. No failures were experienced. Three unexpected failures of these transducers

have occurred during explosions in the reactor. The transducer at the bottom of the core failed on the first explosion. It was replaced, but again the new transducer failed on the third explosion. This mounting at the bottom of the core distorts the transducer more severely than any other, producing a zero unbalance of 12 millivolts (equivalent to 600 psi), which may be a contributory cause of failure. The transducers at the top of the core and on the overflow chamber are the originals and have been subjected to many hydrogen and oxygen explosions without failures. A transducer on the recombiner failed after about a dozen explosions. This failure has not been explained.

III. THERMOCOUPLE INVESTIGATIONS

A. BARE WIRE THERMOCOUPLE TESTING

Concurrently with work on pressure transducers, methods of measuring the rapidly-varying fuel solution temperatures were investigated. Although devices such as resistance thermometers can be made with short time constants, they cannot be directly exposed to electrolytes. Once insulation is applied, the time constant becomes long. Certain thermocouples, such as stainless steel and platinum, and platinum and platinum-10% rhodium, could be exposed to the corrosive uranyl sulphate and sulphuric acid solution and still give the same emf vs temperature curve as in ordinary water. The fact that the thermocouple junction has a resistance of only 1 to 2 ohms or less, reduces the galvanic voltage to a negligible value. A chromel-alumel junction was found unsatisfactory because of a corrosive attack on the alumel. Most common thermocouples have a similar disadvantage.

The problem of fast response was attacked by making junctions of successively finer wires. It was found that clean junctions of 316 stainless steel and platinum could be easily made by spot welding. These gave a thermoelectric emf slightly less than that given by Pt and Pt-10% Rh. Junctions of Pt and Pt-10% Rh could also be spot welded with slightly more difficulty. The first junctions tested for time constant were 10-mil Pt —13-mil stainless steel. They had a time constant of about 15 milliseconds. As the thermocouples were constructed of finer and finer wires and as the time constants became correspondingly shorter, it became evident that a special mechanism would be needed to test the time constants of these junctions. To satisfy this need, a thermocouple tester (Figure 33) was built. This tester consists of an oil reservoir with an electric heater, a pump, a jet, and a shutter driven by a rotary solenoid. Hot silicone oil is circulated by the pump so that an oil jet impinges on the shutter with a velocity of about 100 inches per second. A nitrogen stream is directed at the thermocouple junction to be tested to keep it clean and cool. On the closing of a contact, the rotary solenoid quickly rotates the shutter so that it no longer intercepts the oil stream, which then impinges on the thermocouple junction, producing a temperature step. A whisker makes contact with

Figure 33. Thermocouple Tester

a pin on the shaft of the rotary solenoid to trigger the signal recording device. A Hughes Memoscope was normally used as the recording instrument. Using this system, time constants [the time to reach a fraction $(1 - 1/e)$ of the temperature step] of 0.7 millisecond average for 1 mil - 1 mil junctions and 0.5 millisecond for 0.5-mil diameter junctions were determined.

B. CONSTRUCTION OF SMALL FAST RESPONSE THERMOCOUPLES

Special techniques were developed for the construction of 0.5-mil and 0.2-mil thermocouples. Since they are described in detail in Reference 14, they will be mentioned only briefly here. Using a small drill press, a fixture was set up to hold the fine Pt and Pt-10% Rh wires during spot welding (see Figure 34). One electrode for spot welding was held in the drill press chuck. Its motion was displayed with a dial indicator and its electrode spacing was held to about one wire diameter. The resistance between the electrodes was checked for reproducibility before each weld as an indication of proper pressure and low contact resistance, and the energy output of the spot welder was carefully controlled. Since 0.2-mil wire is too fragile to handle directly, Wollaston wire was used and the silver coating was removed with nitric acid just before spot welding. The junctions were then spot welded into 0.003-inch drilled holes in a 15-mil Pt wire and a 15-mil Pt-10% Rh wire in the thermocouple stem (see Figure 35). These two 15-mil wires were sealed into a Type 347 stainless-steel stem by Corning 0080 glass. A completely-assembled thermocouple ready for installation in the reactor core is shown in Figure 36. Completed thermocouples were pressure tested to 3000 psi and helium leak tested.

A calibration of a thermocouple constructed by this method was made up to 94°C by comparing it with a standard platinum resistance thermometer. The thermocouple was in error by no more than 0.3°C at any point with excellent repeatability. There has been some difficulty with noise pickup in the thermocouple tested in the reactor. The need for a high frequency response differential amplifier with common mode rejection to remove pickup is apparent if the best results are to be obtained.

Figure 34. Drill Press with Fixture for Spot Welding Wires

Figure 35. 1/2 mil Pt - 1/2 mil Pt 10% Rh
Thermocouple Junction and Stem

Figure 36. Fast Thermocouple for Installation in KEWB

IV. SUMMARY AND CONCLUSIONS

A. RESULTS OF THE PROGRAM

After an experimental survey of eight different models of pressure transducers, a system with fast response was developed to measure pressures in the KEWB reactor. The transducers used in the system operate in an environment which presents a high radiation level but which has temperatures that are quite low for a reactor. Thus they would not be suitable for use in a power reactor because of the temperature limitation. Since installation of this pressure-measuring system in the KEWB reactor, the recombiner tests and transient experiments have been completed, and observations have been made of explosion pressures.

B. CONTRIBUTIONS OF THE PROGRAM

Two very useful pieces of special equipment were developed in the course of this project. One was the remotely-controlled shock tube, which was used for testing transducers and was operable in the reactor through-tube. The other was the Dual DADEE circuit developed to compensate for ringing and insufficiently fast response in transducers with two degrees of freedom.

APPENDIX I

DERIVATION OF THE HUGONIOT RELATION

Symbols are defined as follows:

ρ_o = density in the unburnt gas

v_o = velocity of the unburnt gas relative to the reaction front

τ_o = specific volume of unburnt gas = $\frac{1}{\rho_o}$

p_o = pressure of unburnt gas

$E^{(o)}$ = complete energy for the unburnt gas

$I^{(o)}$ = complete enthalpy of unburnt gas

ρ_1 = density of the burnt gas

v_1 = velocity of the burnt gas relative to the reaction front

τ_1 = specific volume of burnt gas = $\frac{1}{\rho_1}$

p_1 = pressure of burnt gas

$E^{(1)}$ = complete energy for the burnt gas

$I^{(1)}$ = complete enthalpy of the burnt gas

m = mass flux

By the law of conservation of mass,

$$\rho_o v_o = \rho_1 v_1 = m, \quad \frac{v_o}{v_1} = \frac{\rho_1}{\rho_o}, \quad \text{and} \quad \frac{v_1}{v_o} = \frac{\rho_o}{\rho_1} . \quad \dots (1)$$

By the law of conservation of momentum,

$$p_o + \rho_o v_o^2 = p_1 + \rho_1 v_1^2 = P, \quad \dots (2)$$

where P is the total momentum flux/cm²-sec or pressure. By the law of conservation of energy,

$$E^{(0)}(\tau_o, p_o) + p_o \tau_o + \frac{1}{2} v_o^2 = E^{(1)}(\tau_1, p_1) + p_1 \tau_1 + \frac{1}{2} v_1^2 . \quad \dots (3)$$

Rewriting (2), we have

$$p_1 - p_o = \rho_o v_o^2 - \rho_1 v_1^2$$

and

$$p_1 - p_o = \tau_o \rho_o^2 v_o^2 - \tau_1 \rho_1^2 v_1^2 .$$

Then, since $\rho_o^2 v_o^2 = \rho_1^2 v_1^2$, from (1), we obtain

$$\frac{p_1 - p_o}{\tau_1 - \tau_o} = -\rho_o^2 v_o^2 .$$

We next eliminate the velocities in equations (1), (2), and (3):

$$E^{(0)} - E^{(1)} = p_1 \tau_1 - p_o \tau_o + \frac{1}{2} v_1^2 - \frac{1}{2} v_o^2 . \quad \dots (4)$$

Multiplying (2) by τ_1 solving for v_1^2 and noting that $\rho_o v_o = \rho_1 v_1$, we obtain

$$v_1^2 = \tau_1 p_o + \frac{v_1}{v_o} v_o^2 - \tau_1 p_1 .$$

Multiplying (2) by τ_o , solving for v_o^2 , and again noting that $\rho_o v_o = \rho_1 v_1$, we obtain

$$v_o^2 = \frac{v_o}{v_1} v_1^2 - \tau_o p_o + \tau_o p_1 .$$

Subtracting and simplifying yields

$$v_1^2 - v_o^2 = \tau_1 p_o - \tau_1 p_1 + \tau_o p_o - \tau_o p_1 . \quad \dots (5)$$

Dividing (5) by 2 across the line and substituting in (4), there results

$$\begin{aligned}
 E^{(0)}(\tau_0, p_0) - E^{(1)}(\tau_1, p_1) &= p_1 \tau_1 - p_0 \tau_0 + \frac{1}{2} \tau_1 p_0 - \frac{1}{2} \tau_1 p_1 + \frac{1}{2} \tau_0 p_0 - \frac{1}{2} \tau_0 p_1 \\
 &= \frac{1}{2} \tau_1 p_1 - \frac{1}{2} \tau_0 p_0 + \frac{1}{2} \tau_1 p_0 - \frac{1}{2} \tau_0 p_1 \\
 &= \frac{1}{2} [p_1 (\tau_1 - \tau_0) + p_0 (\tau_1 - \tau_0)],
 \end{aligned}$$

or

$$E^{(1)}(\tau_1, p_1) - E^{(0)}(\tau_0, p_0) = -\frac{1}{2} (\tau_1 - \tau_0) (p_1 + p_0) \quad \dots (6)$$

This is the Hugoniot relation. To express this in terms of enthalpy, use

$$I^{(1)} = E^{(1)} + p_1 \tau_1$$

and

$$I^{(0)} = E^{(0)} + p_0 \tau_0.$$

Then

$$I^{(1)} - p_1 \tau_1 - I^{(0)} + p_0 \tau_0 = -\frac{1}{2} (\tau_1 - \tau_0) (p_1 + p_0)$$

or

$$\begin{aligned}
 I^{(1)} - I^{(0)} &= p_1 \tau_1 - \frac{1}{2} \tau_1 p_1 - \frac{1}{2} \tau_1 p_0 - p_0 \tau_0 + \frac{1}{2} \tau_0 p_1 + \frac{1}{2} \tau_0 p_0 \\
 &= \frac{1}{2} \tau_1 p_1 - \frac{1}{2} \tau_1 p_0 - \frac{1}{2} \tau_0 p_0 + \frac{1}{2} \tau_0 p_1 \\
 &= \frac{1}{2} (\tau_1 + \tau_0) p_1 - \frac{1}{2} (\tau_1 + \tau_0) p_0,
 \end{aligned}$$

or, finally,

$$I^{(1)} - I^{(0)} = \frac{1}{2} (\tau_1 + \tau_0) (p_1 - p_0) \quad \dots (7)$$

Using (1) and (7), and knowing ρ_0 , v_0 , v_1 , and the enthalpy change, the pressure rise in the detonation shock front can be calculated.

APPENDIX II

EXPLOSION PRESSURE TRANSDUCER SPECIFICATIONS FOR THE KEWB EXPERIMENT

Specification:

For unbonded strain gauge, four-arm resistance bridge type pressure pickup for use in KEWB. Large case. Flange mounted model.

1. Case Design

- a. The body of the transducer will be a cylinder between 0.605 and 0.625 inch in diameter for large-case transducer with the pressure sensitive diaphragm on one end of the cylinder and electrical connections on the other end.
- b. The transducer body will have an integral mounting ring 0.725 to 0.750 inch in diameter set back of diaphragm 0.125 to 0.225 inch for large case size.
- c. The transducer will be mounted by clamping the mounting ring between a machined boss and mounting flange with a gold gasket seal being placed on diaphragm end of mounting ring. (Note: mounting flange and gold gasket to be supplied by AI.)
- d. The portions of the transducer exposed to fuel solution, that is, the diaphragm end back to and including the mounting ring, must be of a one-piece design. If any joint occurs in this region, it must be a welded joint. Brazing, silver solder, soft solder, or other types of seals are not acceptable.
- e. The case must be Type 321, 347, or 316 ELC stainless steel, if welding is used. Type 316 can be used in one-piece case diaphragm design with no welds.
- f. For absolute pressure pickups, all electrical connections, seals, and assembly joints behind the mounting ring must be designed to withstand an internal pressure in the pickup of 300 psia in the event of diaphragm failure or leak. Solder joints must not be relied upon for mechanical strength, but may be used to obtain a gas-tight seal. (This section is not applicable to gauge type transducers.)

2. Transducer Electrical Specification

- a. Four-arm resistive bridge with a bridge impedance between 250 and 500 ohms.
- b. Bridge excitation: up to 7 volts dc or 7 volts rms for carrier.
- c. Output voltage: 30 to 50 millivolts output at 7 volts excitation at rated full-range pressure.
- d. Electrical insulators in the transducer must be glass, ceramics, sapphires, quartz, or an equivalent type of material which is not readily subject to excessive radiation damage. In general, teflon or other plastics are not satisfactory.

3. Transducer Response Specifications

- a. Natural frequency: minimum acceptable 20 kc, harmonics are to be kept to a minimum, not more than one harmonic to be detectable and its frequency not to be above 105 kc. (Refer to $2H_2 + O_2$ explosion pictures of PA217TCa-1M-350 serial No. 7, 4/28/58.)
- b. Pressure limits: the unit must be able to withstand a static pressure overload to 150% of rated full-scale output without change of calibration in excess of 2% of full scale.
- c. Hydrogen-oxygen explosions: the transducer must not be damaged when subjected to shock waves from 5 stoichiometric hydrogen-oxygen explosions in gas with an initial pressure of 1.25 atmospheres; the explosions have a pressure-rise time of much less than a microsecond. A 1500-psi transducer should be used for these tests and should be hit head-on by the shock front. "No damage" implies that the transducer's output voltage vs pressure curve will not change by more than 5% after such explosions and that the response in all other respects will be equivalent to the pre-explosion specifications.
- d. The compensated temperature range is 0 to 110°C or 32 to 230°F.
- e. Zero shift: less than 0.03% FS/°F over compensated temperature range. Zero unbalance to be less than 2 millivolts with 7 volts applied to bridge.

- f. Thermal coefficient of sensitivity: less than 0.02% FS/°F over compensated temperature range.
- g. Linearity and hysteresis: deviation will be less than 1% FS output.
- h. Acceleration response: vibratory response to be less than 0.02% FS/g for frequencies to 2000 cps.

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