Ultrasonic Measurement of Fracture Toughness of a Nuclear Grade Steel

A. N. SINCLAIR and T. CHAU
Department of Mechanical Engineering, University of Toronto, Canada, M5S 1A4

ABSTRACT

Ultrasonic attenuation measurements were made on SA106 grade B steel in an attempt to find a nondestructive method for measuring its fracture toughness. The situation is complicated by the directional dependence of K_{IC} in this material. The attenuation measurements showed considerable scatter among the 14 specimens inspected, and no apparent correlation with toughness. Reasons for the discrepancy between this result and those of other researchers on different materials are explored.

KEYWORDS

ultrasonic attenuation, fracture toughness, nondestructive testing, nuclear grade steel, stress wave

INTRODUCTION

The measurement of the plane strain fracture toughness K_{1C} of a specimen has traditionally been considered a destructive operation. When this fact is combined with the various constraints imposed by the ASTM testing standard E399, several fundamental problems emerge if it is desired to ensure a minimum toughness value for an engineering component:

(a) First, the destructive nature of the test prevents the measurement of K_{IC} on the actual component in question. Instead, extra copies of the component must be made available in order to provide appropriate material for test specimens.

(b) In order to guarantee plane strain conditions, K_{IC} test specimens must be made to a prescribed minimum thickness. It may be impossible to manufacture such specimens out of a thin-walled component such as a turbine disk or small-diameter high pressure pipe.

(c) The standard ASTM procedure for measuring K_{IC} requires the specimen to be pre-cracked with a straight crack front. This can be difficult to achieve, particularly with large-grained material.

To address these shortcomings, several researchers have attempted to develop a nondestructive method for measuring fracture toughness based on ultrasonic attenuation measurements. Some early success in this area was achieved, using several grades of maraging steel, titanium alloys, and tungsten carbide (Vary and Hull, 1974, 1983, Vary, 1978). Although his preliminary correlations between K_{IC} and frequency dependent attenuation coefficient α were largely empirical, a stress wave model was developed to assist in the analysis. The model is based on the premise that unstable fracture is precipitated by the generation of stress waves upon the initiation of a crack at a defect or other nucleation site. These stress waves in turn promote crack initiation at other nucleation sites, resulting in a cascading effect and ultimate failure (Fu, 1980, Vary, 1979, Fu, 1983). The question as to whether these stress waves will have sufficient energy to reach a neighboring nucleation site and precipitate fracture depends on (1) the average distance between such sites, and (2) the extent of wave energy attenuation during propagation in a grained structure. Information on both these points can be derived from ultrasonic attenuation measurements; hence the possible connection between K_{IC} and attenuation coefficient α.

The major challenge to this technique is the evaluation of K_{IC} based solely on the limited microstructural information obtained from the attenuation measurements. As shown by other researchers, this last task may not always be possible (Klinman et al., 1980). It was demonstrated (Nadeau et al., 1984) that by varying the temperature of Type 403 stainless steel from $-60°C$ to $+40°C$, the fracture toughness changed by a factor of 3; however, this change in K_{IC} was not accompanied by a corresponding change in grain size distribution, and therefore correlated very poorly with ultrasonic attenuation measurements. Sinclair and Eng (1987) observed some correlation between K_{IC} of Type A357 cast aluminum and α, but the correlation was not consistent with Vary's model.

These results indicate that the fracture process is too complicated to assume a simple, universal relationship between K_{IC} and α. The limited successes that were achieved, however, indicate that in some cases a **perturbation** of toughness properties from a reference condition may be accompanied by a corresponding change in microstructure. In such cases, ultrasonic attenuation may be a viable tool for quality control, e.g., detection of modifications in the quenching procedure in a heat treatment cycle. Related to this last point, ultrasonics could also be used as a research tool for studying the interrelation between grain size morphology and fracture properties (Sinclair and Eng, 1987, Reynolds and Smith, 1984).

In this paper, the relationship between fracture toughness and ultrasonic attenuation shall be investigated in a nuclear grade pipe steel. The emphasis will be on the correlation between the the non-isotropic nature of K_{IC} for this material, and directional dependence of the attenuation coefficient.

THEORY

Assuming that the vast bulk of ultrasonic attenuation is caused by grain boundary scattering in metals, a scattering regime can be defined according to the relative size of wavelength λ, and scattering body mean chord length $\bar{D}$. For this study, primary interest is focussed on the Rayleigh regime for which $\lambda \gg \bar{D}$:

$$\alpha = C_1 \frac{<D^6>}{<D^3>} f^m = C_2 f^m \tag{1}$$

where m is approximately equal to 4, $\bar{D}$ is the average value of D, and $<D^i>$ is the mean of the i^{th} power of D. Reynolds and Smith(1984) have developed an experimental procedure for determining the boundaries of the Rayleigh regime for a given material, and evaluating the parameters of eq. (1).

Determination of K_{IC} from an attenuation measurement requires several major assumptions which cannot be justified for all engineering materials. It is assumed that a critical energy density is required to initiate fracture of a crack nucleation site. The bulk of this energy is obtained from the elastic strain energy K_c^2/σ_y, originating from the remotely applied load on the system. The remainder comes from stress wave energy originating from the fracture of a neighboring nucleation site a distance l away. Assuming the stress wave spectrum to be broadband at the point of origin, and the ultrasonic attenuation coefficient to be of the form $\alpha = cf^m$, the stress energy spectrum $e(\lambda)$ reaching the neighboring nucleation site can be shown to be (Vary, 1979):

$$e(\lambda) = B_1 \frac{\delta l c_L \beta}{E' \lambda^2} \tag{2}$$

where δ is the typical size of a crack nucleation site, and is of the same order of magnitude as the parameter $\bar{D}$. The effective elastic modulus E' and sound velocity c_L are material properties, and β is the derivative of the attenuation coefficient α with respect to frequency. The parameter B_1 is a material constant proportional to the stress wave energy density Q released upon cracking of a nucleation site of dimension δ:

$$Q = B_1 \, \delta/2E' \tag{3}$$

It is assumed that high attenuation will render $e(\lambda)$ negligible for wavelengths less than δ, so that attention may be confined to the Rayleigh regime. Integrating eq. (2) for wavelengths greater than δ yields the total stress wave energy e_{tot} available to promote crack initiation at a neighboring nucleation site:

$$e_{tot} = \int_{\delta}^{\infty} e(\lambda)\, d\lambda = \frac{B_1 \, l}{E'} \left[\frac{c_L \beta}{m} \right] \tag{4}$$

where β is evaluated at the wavelength $\lambda = \delta$.

It is assumed that unstable fracture results when the ratio of e_{tot} divided by the elastic strain energy due to external loading of the specimen reaches a prescribed value B_2. Assuming plane strain conditions, this gives:

$$\frac{e_{tot}}{K_{IC}^2/\sigma_y} = B_2 \tag{5}$$

Combining the above equations, and using LEFM to express E' in terms of K_{IC} and σ_y, Vary (1979) obtained:

$$\left[\frac{K_{IC}}{\sigma_y} \right]^2 = \psi_1 \left[\frac{c_L \beta}{m} \right]^{0.5} , \quad \psi_1 = \left[\frac{4}{\pi} B_1 B_2 \, l \, \delta_c \right]^{1/2} \tag{6}$$

where δ_c is the critical crack opening displacement. The crucial assumption is that ψ_1 is invariant over the range of materials and testing environments in question. From eq. (6), this assumption immediately comes under suspicion on two counts:

1. Certain environmental factors, such as a large increase in temperature, could clearly cause a marked change in the toughness and yield strength parameters on the left side of the equation. The ultrasonic parameter $c_l \beta/m$, however, would not be altered if the grain structure were not disturbed. Therefore, the parameter ψ_1 could not remain constant.
2. From eq. (6), it can be seen that ψ_1 is dependent on the critical crack opening displacement δ_c. In general, δ_c can be expected to change when K_{IC} is altered, thereby perturbing the value of ψ_1.

The second of these two points can be addressed by using LEFM to express δ_c in terms of K_{IC}. Eq. (6) can then be recast in the form:

$$\left[\frac{K_{IC}}{\sigma_y}\right]^2 = \psi_2 \left[\frac{c_L \beta}{m}\right]^{1.0} \quad , \quad \psi_2 = \frac{B_1 B_2 l}{E'} \tag{7}$$

This equation is similar to the one developed by Fu (1983). The selection of eq. (6) or (7) would be based on the relative stabilities of the parameters ψ_1 and ψ_2 over the range of test conditions.

In addition to the stability of the parameter ψ_1 or ψ_2, there exist additional criteria to assess the applicability of these models to a testing program. First, experimental measurements of the attenuation coefficient, as a function of λ, should yield the relationship given by eq. (1) with $m \approx 4$, if attenuation is truly dominated by Rayleigh scattering. Experience has shown, however, that m tends to range from a value of about 1 up to 3 (Vary and Hull, 1983, Vary, 1978, Generazio, 1984). This implies that the scattering regime is not well-defined, likely due to a wide range of scatterer sizes. Under theses conditions, the theoretical development given above quickly breaks down. Perhaps the most crucial check is based on an understanding of the fracture process itself. Vary found that eq. (6) worked well for tungsten carbide, for which it is known that the size of the carbide particles plays a dominant role in both the material toughness, and attenuation coefficient (Vary and Hull 1983).

EXPERIMENT

The theory presented in the last section will now be applied to study the microstructural characteristics that affect the fracture properties of a nuclear grade steel. The study is somewhat complicated by the non-isotropy of the material, resulting in direction-dependent values of K_{IC}. The objective is to determine whether ultrasonic attenuation measurements can be correlated with the microstructure, and the directional dependence of K_{IC}.

Materials

The material in question is ASME SA-106 grade B seamless pipe steel, used in the high pressure coolant piping of nuclear power plants. Compact tension specimens were cut from six heats of pipe, of outer diameter 24 inches (61 *cm*) and wall thickness 2.5 inches (6.4 *cm*). Four specimen orientations were used labeled *A*, *B*, *C* and *D*, as shown in Fig. 1 ; each orientation features a crack on either the radial-longitudinal or radial-circumferential plane. Tensile tests were performed at a temperature of 293 *K* on samples from each heat corresponding to various crack plane directions. Results of these tests are given in Table 1. The results indicate no significant difference in the tensile properties of specimens oriented in the longitudinal direction of the pipe, as opposed to the circumferential direction. The slope of the load-displacement curves gave an average value of Young's modulus *E* of 208 *GPa*.

Test Procedure

Due to the high ductility of this steel, direct measurement of K_{IC} is prone to error, in that strict test validity requirements as quoted in ASTM E399 may not be met. Instead, *J*-integral measurements were performed according to ASTM E813, and then values for K_{IC} estimated from the LEFM relation:

$$K_{IC} = \sqrt{J_{IC} E'} \tag{8}$$

Figure 2 shows a summary of average $J-\Delta a$ curves representing the four specimen orientations in heat #3.

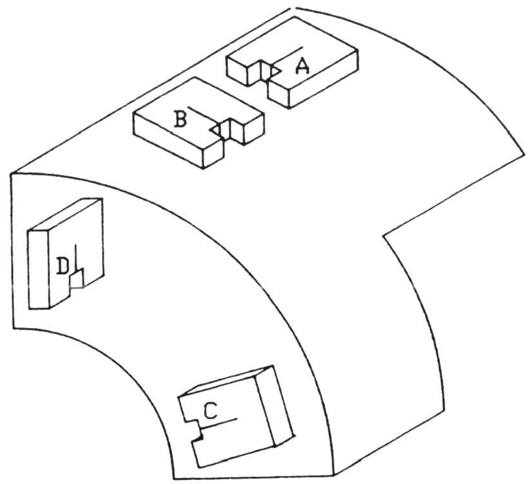

Fig. 1. Orientations of compact tension specimens (from Gilbert, 1988).

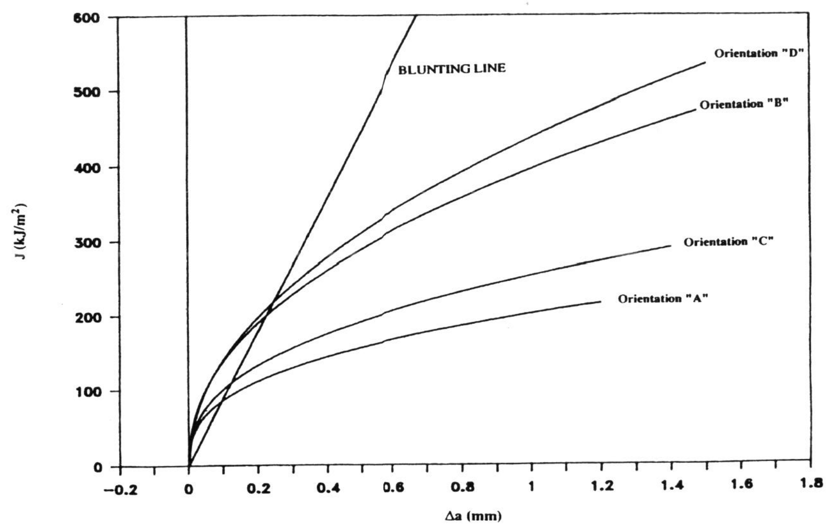

Fig. 2. J-R curves for SA106 grade B compact tension specimens (from Gilbert, 1988).

Ultrasonic attenuation measurements were then performed on the specimens, with the direction of ultrasound travel chosen to be parallel with postulated stress wave propagation. Attenuation was measured with 4 different probes ranging in central frequency from 4 up to 20 MHz. Contact probes were used in a pitch-catch mode; the experimental set-up recommended by Canella and Taddei (1987) was adopted, in which a delay line is used on the transmitting probe; this ensured that measurements were conducted in the far field where the effects of beam spreading can be easily accounted for. Immersion tests were also conducted and found to yield results within the experimental scatter expected for attenuation measurements.

Regression analysis was used to find the best values of the parameters C_2 and m corresponding to eq. (1), for each specimen. From this data, a calculation of $(c_L\beta/m)$ was made for each specimen; the relevant data are shown in Table 1. A graph was then constructed of $(c_L\beta/m)$ plotted against $(K_{IC}/\sigma_y)^2$, shown in Figure 3.

Table 1: Ultrasonic and Fracture Test Results on SA-106B Specimens at 293 K

CT Specimen	σ_y (MPa)	σ_{UTS} (MPa)	J_{IC} kN/m	K_{IC} $MPa\sqrt{m}$	m	$\left[\frac{c_L\beta}{m}\right]$
1A[a]	311[b]	561	104	155	2.02	0.0198
1A	311	561	97	149	1.99	0.0196
2A	324	530	190	208	2.11	0.0203
2A	324	530	111	159	2.07	0.0204
3A[c]	288	600	113	161	2.14	0.0187
3B	288	600	280	253	2.15	0.0190
3C	288	600	180	203	2.16	0.0179
3D	288	600	270	248	2.20	0.0190
4B	323	561	140	179	2.08	0.0205
4B	323	561	174	199	2.08	0.0217
5B	348	547	421	309	1.91	0.0216
5B	348	547	385	296	1.86	0.0204
6B	367	516	275	250	2.26	0.0218
6B	367	516	214	221	2.24	0.0231
ASME Spec.	>240	>415				

[a] Specimen designation XY: Integer X refers to heat number from which specimens were manufactured. Letter Y indicates direction of crack propagation, according to Figure 1.
[b] Values for σ_y and σ_{UTS} were obtained by tensile tests, using specimens oriented perpendicular to the crack plane of the compact tension specimen. Compact tension specimens designated A and C feature cracks in the same plane; therefore σ_y and σ_{UTS} are identical. Similarly, specimens in B and D directions have matched tensile properties.
[c] Material corresponding to heat #3 was purchased from a different manufacturer from the other specimens.

ANALYSIS

Figure 3 clearly demonstrates that variations in attenuation properties of all samples of SA-106B were essentially independent of the parameter $(K_{IC}/\sigma_y)^2$, and of the direction of wave propagation. The large scatter seen in the toughness parameter is typical for test results with this steel; the J integral curves tend to show appreciable variation from specimen to specimen, in addition to their directional dependence. This in turn led to large variations in K_{IC} among the specimens tested. However, as was the case for Nadeau etal (1984), large variations in toughness were not accompanied by a corresponding change in ultrasonic attenuation characteristics. Neither eq. (6) nor (7) can therefore be applied to describe the test results shown in Fig. 3.

The reason lies in the understanding of the factors affecting K_{IC} in the SA-106B steel. Micrographs indicate that the grain structure is close to isotropic. The ASME specification calls for a final heat treatment of this steel after it has been drawn, which results in the recrystallization process that produces the isotropic grain structure. This isotropy is confirmed by pole figures which indicate a random orientation of crystal axes (Gilbert, 1988).

The non-isotropy in toughness values is believed to originate from small inclusions that have been drawn out into "stringers" in the longitudinal direction of the pipe (Fig. 4). These inclusions result in fracture at a low level of applied stress for cracks in the radial-longitudinal plane (orientations *A* and *C*). The directional effect of these stringers is dramatized by an examination of the fracture surfaces for for specimens of orientations *A* and *C* (Fig. 4). Orientations *B* and *D* (radial-circumferential plane) are capable of considerably more stable crack growth before ultimate failure, and would therefore be more supportive of a leak-before-break design philosophy.

The non-isotropic fracture properties are related to the presence of large inclusions which are not consistent with a Rayleigh scattering model. As a result, eqs. (6) and (7) break down, and there is no apparent correlation between α and the directional dependence of K_{IC} in SA106 grade B steel. It is also noteworthy that values of the parameter m were found to be closer to 2 than 4 as predicted for Rayleigh scattering (perhaps due to the large inclusions, or experimental difficulties in measuring α accurately). It is evident that a clear understanding of both the ultrasonic attenuation and fracture mechanisms in a particular material is required before the use of attenuation measurements to determine toughness can be recommended.

SUMMARY

No correlation was found between the directional dependence of fracture properties of SA-106B steel and directional variation in ultrasonic attenuation. This is because small inclusion stringers, which have negligible effect on the attenuation coefficient α, are believed to have a dominant influence on the value of K_{IC} for this material. These findings indicate the need for a solid understanding of the factors controlling fracture properties before nondestructive measurement of K_{IC} can be profitably pursued.

ACKNOWLEDGEMENTS

This work was supported by grants from the University of Toronto Center for Nuclear Engineering, the Canadian Natural Sciences and Engineering Research Council, and also by a contract from the Canadian Atomic Energy Control Board. Gratitude is expressed to Ontario Hydro Research Department which provided a portion of the SA-106B test data, and to K. Gilbert of the University of Toronto for conducting additional tests.

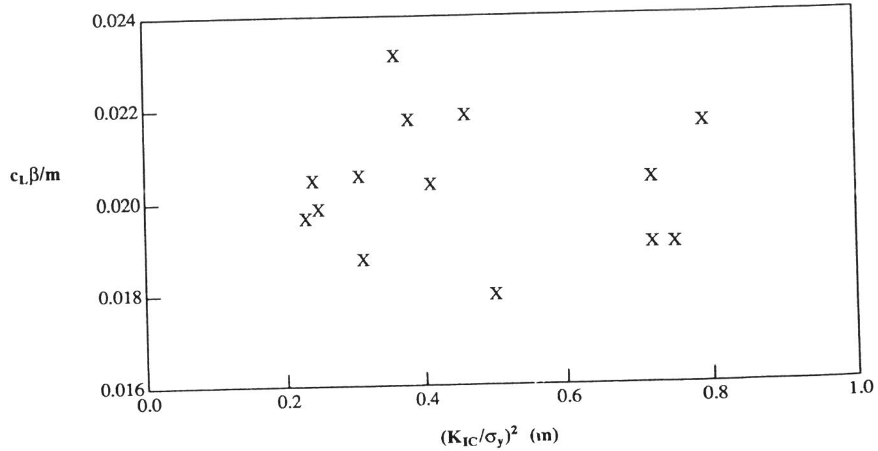

Fig. 3. Ultrasonic parameter ($c_L\beta/m$) versus toughness parameter $(K_{IC}/\sigma_y)^2$.

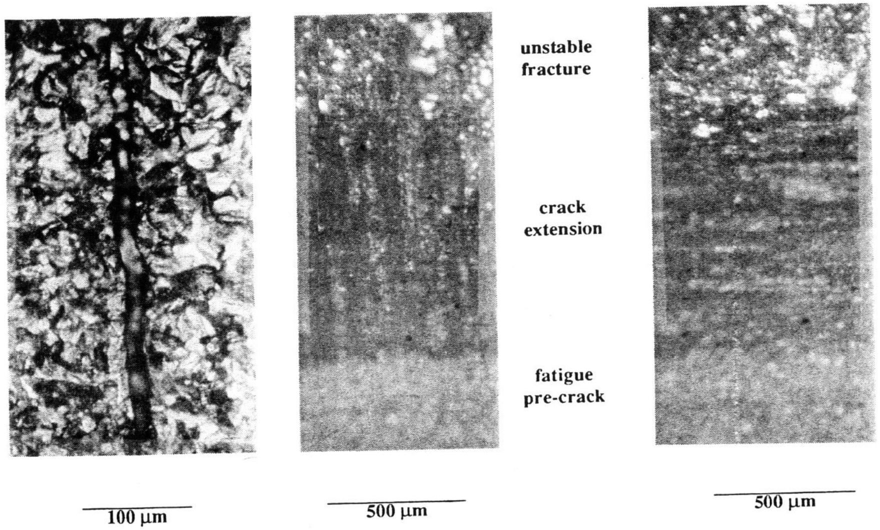

Fig. 4. Inclusion stringers (left) aligned in the longitudinal direction of the pipe lead to non-isotropic fracture characteristics: crack face of a type *A* specimen (center) as opposed to a type *C* specimen (right).

REFERENCES

Canella, G. and Taddei, M. (1987). M. Correlation Between Ultrasonic Attenuation and Fracture Toughness. In: *Nondestructive Characterization of Materials II* (J.F. Bussiere, J.P. Monchalin, C.O. Ruud, and R.E. Green, Jr., eds.), pp. 261-269, Plenum Press, New York.

Fu, L.S. (1980). On the Feasibility of Quantitative Ultrasonic Determination of Fracture Toughness, NASA, Cleveland, Report 3356.

Fu, L.S. (1983). On Ultrasonic Factors and Fracture Toughness, *Eng. Frac. Mech.* 18, 59-67.

Generazio, E.R. (1983). Ultrasonic Verification of Microstructural Changes Due to Heat Treatment, NASA, Cleveland, Report CP-2383.

Gilbert K.R. (1988). An Experimental Investigation into Crack Propagation in Tough Ductile Materials, undergraduate thesis, Department of Mechanical Engineering, University of Toronto.

Ho, E.T.C. and McGraw, M.J. (1986). Tensile Properties of Sa-106 Grade B and SA105 Darlington Primary Heat Transport Piping Material at 293 and 523 *K*, Ontario Hydro Research Division, Report 86-11-K.

Klinman, R., Webster, G.R., Marsh, F.J., and Stephenson, E.T. (1980). Ultrasonic Prediction of Grain Size, Strength, and Toughness in Plain Carbon Steel, *Mat. Eval.*, 38, 26-32.

Mukherjee, B. and Carpenter, D. (1987). Darlington Leak Before Break Material Test Program J-Resistance Curves, Vol. 1, Ontario Hydro Research Division, Report 87-232-K.

Nadeau, F., Bussiere, J.F., and Van Drunen, G. (1984). On the Relation Between Ultrasonic Attenuation and Fracture Toughness in Type 403 Stainless Steel, *Mat. Eval.*, 38, 101-104.

Reynolds, W.N. and Smith, R.L. (1984). Ultrasonic Wave Attenuation Spectra in Steel, *J. Phys. D: Appl. Phys.*, 17 109-116.

Sinclair, A.N. and Eng, H. (1987). Ultrasonic Determination of Fracture Toughness. In: *Nondestructive Characterization of Materials II* (J.F. Bussiere, J.P. Monchalin, C.O. Ruud, and R.E. Green, Jr., eds), pp. 251-259, Plenum Press, New York.

Vary, A. and Hull, D.R. (1974). Interrelation of Material Microstructure, Ultrasonic Factors, and Fracture Toughness of a Two-Phase Titanium Alloy, *Mat. Eval.*, 32, 309.

Vary, A. (1978). Correlations Among Ultrasonic Propagation Factors and Fracture Toughness of Metallic Materials, *Mat. Eval*, 26, 55-64.

Vary, A. (1979). Correlations Between Ultrasonic and Fracture Toughness Factors in Metallic Materials. In: *ASTM STP 677*,, American Society for Testing and Materials, Philadelphia, 563-578.

Vary, A. and Hull, D.R. (1983). Ultrasonic Ranking of Toughness of Tungsten Carbide, NASA, Cleveland, Report 83358.

Venter, R.D., Sinclair, A.N., and McCammond, D. (1987). Crack Propagation in Tough Ductile Materials (Phase I), Atomic Energy Control Board, Ottawa, Report INFO-0254-1.