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REPORT DOCUMENTATION PAGE

AD-A217 667

1b. RESTRICTIVE MARKINGS	
3. DISTRIBUTION/AVAILABILITY OF REPORT	Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	
5. MONITORING ORGANIZATION REPORT NUMBER(S)	ARO 22678.3-MS
6a. NAME OF PERFORMING ORGANIZATION	North Carolina State University
6b. OFFICE SYMBOL (If applicable)	
7a. NAME OF MONITORING ORGANIZATION	U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code)	Department of Nuclear Engineering Box 7909 Raleigh, NC 27695-7909
7b. ADDRESS (City, State, and ZIP Code)	P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	U. S. Army Research Office
8b. OFFICE SYMBOL (If applicable)	
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)	P. O. Box 12211 Research Triangle Park, NC 27709-2211

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Magnetic Vapor Shield Mechanism for Protection of Material Surfaces Exposed to High Heat Load

12. PERSONAL AUTHOR(S)
Dr. John G. Gilligan

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 1/86 TO 9/89	December 11, 1989	35

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

High heat flux; surface erosion; ~~vapor shield;~~ magnetic vapor shield; melting/ablation. (EDC)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This ~~The~~ project has been successful in predicting decreased erosion of surfaces exposed to high heat fluxes under railgun or electromagnetic (EM) launcher conditions. The significant reduction has come as a result of the proper modeling of the vapor shielding (VS) effect. Favorable comparison with experimental results supports our conclusion. A further decrease in surface erosion should come as a result of an applied magnetic field which should reduce turbulence in the VS boundary layer. Preliminary experimental measurements support this claim, but further theoretical work must be done which would include 2-D, and turbulent effects.

Keywords: Plasmas physics; Mathematical models; Radiation transport.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS
21. ABSTRACT SECURITY CLASSIFICATION	Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	
22b. TELEPHONE (Include Area Code)	
22c. OFFICE SYMBOL	

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

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MAGNETIC VAPOR SHIELD MECHANISM FOR PROTECTION OF MATERIAL SURFACES EXPOSED TO HIGH HEAT LOAD

FINAL REPORT

By

J. G. Gilligan

December 11, 1989

U. S. ARMY RESEARCH OFFICE

(DAAL03-86-K-0029)

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ABSTRACT

The project has been successful in predicting decreased erosion of surfaces exposed to high heat fluxes under railgun or EM launcher conditions. The significant reduction has come as a result of the proper modeling of the vapor shielding (VS) effect. Favorable comparison with experimental results supports our conclusion. A further decrease in surface erosion should come as a result of an applied magnetic field which should reduce turbulence in the VS boundary layer. Preliminary experimental measurements support this claim, but further theoretical work must be done which would include 2-D, and turbulent effects.

Final Report

MAGNETIC VAPOR SHIELD MECHANISM FOR PROTECTION OF MATERIAL SURFACES EXPOSED TO HIGH HEAT LOAD

Contract Period (January 1986 - September 1989)

John G. Gilligan
Department of Nuclear Engineering
North Carolina State University

INTRODUCTION

This final report summarizes theory and numerical modelling work accomplished on our project entitled "Magnetic Vapor Shield Mechanism for Protection of Material Surfaces Exposed to High Heat Load" (DAAL03-86-K-0029). The time period of the contract ran from January 1986 through September of 1989 with total support of approximately $151,000. A two-year contract renewal proposal (~ $120,000) has been submitted (April 1989) and is currently being evaluated by the ARO. Support for the project has come from both the engineering (David Mann) and materials (Andrew Crowson) divisions at ARO. A larger companion project for experimental verification and testing of the magnetic vapor shield (MVS) mechanism has been funded by the SDI/IST through the ARO at a level of $300,000 from July 1987 through December 1989. It is likely that funding of that project (through the SDC) will continue at a level of $612,000 from January 1990 through December 1993.

Overview

Plasma-material surface interaction is of vital importance to research areas supported by the Department of Defense. Plasma etching and vapor deposition techniques are used in the fabrication of microelectronics devices. Combustion plasmas are present in propellant systems and engines. Vaporization plasmas are created when material surfaces are exposed to high heat flux in gun barrels, plasma switches, EM launchers (railguns) and electrothermal guns. The goal of our research is to computationally model and experimentally verify the Magnetic Vapor Shield (MVS) concept[1-2] as a means of protecting material surfaces from ablation and melting caused by extremely high heat loads. The basic vapor shield mechanism has been observed by our group in an electrothermal gun[2] (SIRENS) and by Keefer in an EM launcher[3]. The important role of ablation in railgun operation has been reviewed by Parker[4].

The basic senario can be visualized as exposing selected sample materials (insulators, conductors, semiconductors) to a plasma source equivalent to the high heat fluxes experienced in many applications such as gun barrels, switches and railguns. A simple vapor shield (See Fig. 1) resulting from ablated surface material is fairly common when high heat or particle fluxes are present. However, the idea of using magnetic fields to actively control transport coefficients and suppress turbulence under these extreme conditions is relatively unexplored.[1-2] The critical questions to be addressed are whether reducing the vapor thermal conductivity (dominated by electron collisions) will decrease the total heat load on the material surface and whether magnetic fields can be made sufficiently strong so as to reduce cross-field turbulence. Calculational evidence obtained thus far suggests that both questions can be answered in the affirmative.

Of special interest to the ARO has been the ablation of internal insulators and electrodes exposed to the radiation from the accelerating plasmas in railguns. These devices have strong self-induced magnetic fields. The MVS concept predicts that if sufficient magnetic field is present at the material surface, then the ablated plasma transport and covection coefficients can be drastically reduced resulting in less energy being transferred to the surface. In turn, the energy is re-directed into axial convective particle transport or photon radiation transport away from the localized area. It is obvious that the viability of the MVS concept is dependent on the delicate balance between the energy flows, electromagnetic radiation, particle convection, and conduction. Hence, for a computational analysis, the coupled energy, momentum and particle balance equations must be solved simultaneously and self-consistently.

Goals of Project

- To understand and control the basic energy transport phenomena in the VS at a material surface under high heat flux.
- To explore the effect of a strong magnetic field in decreasing surface erosion under high heat flux.
- To model the MVS mechanism and to compare with experimental results.

Principal Project Accomplishments (1986-1989)

- Described basic physical mechanisms of the vapor shield (VS) process for protection of surface conditions including necessary conditions.
- Described basic physical mechanisms to enhance the VS effect with strong magnetic field - Magnetic Vapor Shield (MVS).
- Developed 1-D, time dependent heat transfer and phase change code (MELTIT).
- Developed 1-D, time dependent, MHD, radiation transport code (MAGFIRE) to analyze VS and MVS effects.
- Developed 0-D, time dependent, energy and particle balance code (ZEUS) to compare theoretical results with experimental data.
- Demonstrated that radiation transport is one of the most important energy transfer mechanisms in the VS. Further, that flux-limited diffusion theory is adequate to describe the transport.
- Demonstrated with numerical simulation that the VS is much more effective in reducing erosion than previously throught (~ 10% energy transmission through the VS as opposed to ~ 50%).
- Demonstrated that certain materials are resistant to high heat flux damage, namely some ceramics and refractory metals. Some materials have better VS properties than others.

- Simulation of the MVS mechanism was inconclusive in 1-D although experiment has shown a decrease in erosion with increasing magnetic field. Simulation with 2-D is required.

- Comparison of numerical simulation and experiment has been excellent for prediction of erosion depths.

- Eleven conference presentations, nine refereed publications and one invited talk have been given on the vapor shield project (See listing of publications at end of report). Dr. J. Gilligan was awarded the NCSU College of Engineering Alcoa Research Prize for work on the project over the past three years.

- Two masters theses and one Ph.D. thesis have been produced. Two current graduate students are partially or fully supported by the project.

  M.S., 1986, M. Holliday, "Analysis of Surface Material Ablation and Melting Using the Heat Balance Integral Technique" (J. Gilligan and M. Doster, Advisors).

  M.S., 1990, R. Rustad, "Melting and Ablation of the First Wall During a Plasma Disruption" (J. Gilligan, Advisor).

  Ph.D., 1990, D. Hahn, "Energy Transport Through a Plasma Boundary Layer" (J. Gilligan, Advisor).

PROJECT RESULTS AND DISCUSSION

Before the beginning of this project the concept of vapor shielding was established in other fields[5-7] but few detailed calculations had been performed to analyze its effectiveness. Early estimates for the total energy fraction transmitted through the vapor shield, f, were in the range of 50%.[6] However, these results did not necessarily agree with experimental measurements for laser light incident on surfaces which were much lower (10-20%)[7]. The first task of this project was to verify that under the typical conditions experienced in railguns (heat flux, duration, photon spectrum, etc.) that the VS would be optically thick enough to absorb the incident photon radiation. With simple estimates for the vapor production rate and detailed calculations of photon radiation opacities, we were able to determine that there was more than sufficient attenuation of photons in the VS to reduce the incident heat flux.[1] In addition, it was found that magnetic fields, if sufficiently strong, could reduce cross field thermal transport dramatically if turbulence could be suppressed as had already been noted for non-ablative boundary layers.[8]

In order to confirm the initial results, several codes were developed to properly analyze the high heat flux, plasma boundary layer at a surface. The codes and their interrelationships are briefly illustrated in Figure 2. Codes that have been completed and tested are indicated in solid blocks. Codes under development are described in blocks with dashed lines. Interfaces with experimental results are also indicated. Individual code results will now be discussed for the vapor shield effect.

MELTIT: 1-D, Time Dependent, Phase Change and Heat Transfer

In order to calculate the amount of surface material vaporized and/or melted under high heat flux, the 1-D, time dependent code MELTIT was written.[9] The heat balance integral technique was used to model the temperature distribution throughout the surface material. Phase change and resulting moving boundaries were explicitly calculated. In addition, the effects of molten material ejection and vapor redeposition were included. However vapor shielding was not directly modeled in MELTIT. Figure 3 shows typical results generated with the code giving the melt front and left boundary position as a function of time for an incident energy density of 5×10^6 J/m^2 on a 0.5 cm slab of SS 316. The effects of melted material ejection can be seen where 25% of the molten material formed is assumed to be removed. As expected, ejection of molten material not only increases the erosion rate at the left boundary, but increased the melt front velocity since there is less resistance to heat transfer. The ablation rate calculated from MELTIT is an important variable that determines the VS transmission. Different materials were found to experience more ablation for a given incident energy fluence, if they had low thermal conductivity and low sublimation energies (typical of insulators and some ceramics).

MAGFIRE: 1-D, Time Dependent, MHD, Radiation Transport

To analyze the VS mechanism requires simultaneous solution of models of:

- Heat conduction and phase change in the material surface,
- MHD transport of the shielding vapor, including electric and magnetic field effects,
- radiation transport in the shielding vapor,
- incident radiation energy and momentum deposition,
- equation-of-state data for the shielding vapor.

The code MELTIT, previously described, satisfied the first modeling requirement. For the transport of the ablated vapor we employed a 1-D, time dependent Lagrangian MHD code, ZPINCH[10], which incorporates multi-group radiation transport. ZPINCH was adapted to account for vapor creation at the boundary surface, low temperature collisions, a parallel external magnetic field and high magnetic field effects on transport coefficients, and was renamed MAGFIRE.[11]

For the following results, the heat flux was modeled as a blackbody spectrum (divided into twenty energy groups) with a constant intensity given by

$$q_s'' = \sigma T_s^4,$$

where σ is the Stefan-Boltzmann constant and T_s is the source temperature. Values of T_s in the range 2-5 eV were chosen which give heat fluxes of $(1.6\text{-}64.0) \times 10^{10}$ W/m^2 that are typical of railguns. The heat flux is incident on a material surface with a characteristic heat of vaporization.

Shown in Figs. 4 and 5 are density and temperature profiles for the vapor shield as a function of distance from the ablating iron surface (semi-infinite slab geometry) at times of 1, 10, and 100 μs. The incident heat flux is 8.3×10^{10} W/m^2 corresponding to a black body with T_s = 3 eV. The density always remains high immediately adjacent to the ablating surface and then falls off as the outer vapor shield layers expand. The temperature of the shield vapor is low near the surface but then increases away from the surface due to absorption of the incoming radiation. It should also be noted that the average ionization state was found to change ~ 10^{-2} at the surface to over 2.0 in the high temperature zones.

The ablation erosion thickness for various incident radiant fluxes and materials is shown in Table I for 10 μs pulses. Also given is the percent of transmitted energy f through the vapor shield to the material surface. Previous estimates of f not using radiation transport techniques or MHD analysis of the transmitted energy were in the 50% range.[6] Our results, where the transmitted energy ranges from 21% down to 3%, presented a much different picture of vapor shield effectiveness. Thus, the predicted erosion thickness can be up to an order of magnitude less than that estimated with a crude vapor shield model. Typical ablation thicknesses are on the order of microns for various materials in Table I. For higher heat fluxes the transmitted energy fraction decreases because more vapor is produced and it provides a "thicker" shield. No clear-cut erosion resistant material is evident in Table I. Carbon has a relatively high heat of vaporization (7.4 eV) compared to iron (4.3 eV) and copper (3.5 eV). Thus, the carbon vapor shield is somewhat less effective for a given heat flux since less vapor is produced.

The effect of ablation rate on transmitted energy through the vapor shield is shown in Fig. 6. The source spectrum is fixed for a 3 eV blackbody but the intensity is increased or decreased to give different incident radiation fluences for a fixed time of 10 μs. The actual fluence for a 3 eV blackbody over 10 μs is 8.3 10^5 J/m^2. As can be seen, the larger fluences give lower transmission fractions through the vapor shield. This is a result of the larger amount of vapor produced which makes the vapor shield "thicker". It appears there may be saturation of the transmitted energy at higher fluences. Likewise, there may be a cutoff below which no vapor shielding takes place. However, the validity of the radiation transport model that uses the diffusion approximation is in question for the low fluence cases below 10^4 J/m^2. In addition, less vapor is actually produced at the low fluences than in our vapor source model since melting would become more important.

Results from our detailed simulations have revealed that photon radiation transport (absorption and re-emission) is the dominant means of energy transport through the vapor shield. Shown in Figure 7 is the energy fluence reaching the material surface as a function of time. Radiative energy is clearly dominant. However, these simulations only include simple heat conduction through the shield which gives rise to a very small contribution to the total energy fluence. Observations by other researchers indicate that convective turbulence may be as important as radiation in the transfer of energy to the surface.[12] Some of our preliminary simulations with "enhanced" convective transport have indeed indicated that this may be the case.

Since radiation transport plays such an important role in the vapor shield, we have re-examined some of the basic principles used in the radiation transport modeling. In MAGFIRE the radiation diffusion approximation is used. The basic assumption of the diffusion approximation is that the radiation field is isotropic. However this is valid for an optically thick medium only. Near the surface of an optically thick medium, or for optically thin systems, the radiation diffusion equation overestimates the radiation transport. Thus, the diffusion approximation overestimates the radiation flux at the wall surface due to the boundary effect, regardless of the optical property of the vapor shield as a whole. One way to overcome the problem of overestimation is to use a flux limiter. The idea is to alter the diffusion-theory formula for the flux in such a way as to yield the standard result in the high-opacity limit, while simulating free streaming in transparent regions.

A formal solution for the radiative transfer equation was derived in order to compare with the present numerical solution which uses the diffusion approximation. One can obtain an analytic solution of the radiative transfer equation for the steady state case where the temperature and density distributions and also the radiation field are independent of time. It is assumed that the radiation field is weakly dependent on angle to derive the multigroup form of the radiative transfer equation. By integrating the solution $I_g(\Omega)$ over all solid angles, one can calculate the radiant energy flux S_g at the wall surface. In order to compare the equivalent quantities, our one dimensional, time dependent, MHD code MAGFIRE is run first until quasi-steady state is reached, and then by using the profiles of density and temperature calaulated, the analytic solution for the steady state multigroup radiative transfer equation is obtained. The analytic solution consists of two parts, one for the attenuation of the external source radiation, and the other for the radiation from the heated vapor shield plasma.

As shown in Table II, the diffusion model with an isotropic flux limiter (c/4, c≡ speed of light) underestimates the radiation flux compared to the analytic solution. The maximum anisotropy value of c overestimates fluxes and further overestimation would be obtained without a flux limiter at all. By using the flux limiter value of (c/2), there is a relatively good agreement between MAGFIRE and the analytic solutions. This is due to the fact that the radiation field is somewhat anisotropic and has a streaming behavior inside the vapor shield plasma, especially near the wall. Figs. 8 and 9 show the frequency group dependent radiation fluxes at 10 μsec for the flux limiters of (c/4) and (c/2) respectively.

Since MAGFIRE gives the radiation flux as a result of diffusive processes, it is impossible to distinguish the attenuated external radiation source from the radiation emitted and attenuated by the vapor shield plasma. However, analytic solutions show that the attenuated source flux decreases with time due to the increased absorption by the vapor shield plasma, and radiation from the vapor shield increases with time due to the increased temperature of the vapor.

The flux limiter of (c/2) was chosen for the diffusion model, but the net effect, that is, the amount of erosion, is insensitive to the choice of the flux limiter values. Transmission factors for the case of the iron wall with 3 eV blackbody radiation of 10 μsec pulse are 8.9, 10.8, and 12.3%, for the flux limiter values of (c/4), and (c/2), and (c), respectively. The small differences in transmission factors are due to the self limiting mechanism of the vapor shield, that is, the larger energy flux causes more ablation, more vapor shield, and then a smaller flux.

ZEUS: 0-D, Time Dependent Electrothermal Gun Simulation

Since the results from the MAGFIRE code were not directly applicable to experimental observation, the ZEUS code was written to incorporate MAGFIRE results (i.e. predictions for f) in the simulation of the breech (source) region of our electrothermal launcher SIRENS. ZEUS[13] is capable of predicting erosion rates of the breech region surfaces as well as plasma temperatures, densities, pressures, ionization states, etc. and thus becomes the direct link to experimental observations. ZEUS describes the physical behavior of ablation controlled devices using the vapor shield concept. The ZEUS code has demonstrated good agreement with previous steady-state ablation plasma models and experimental results and also yields very reliable predictions for ablation depth in SIRENS.

The 0-D, time dependent code ZEUS includes models for the energy transport, particle transport, resistivity and equations-of-state under local thermodynamic equilibrium. The degree of ionization for the plasma is computed from a modified Saha equation based on arc temperature and density. The input parameters to the code include the initial density, temperature, charge state of the plasma and the time history of the discharge current. The code has the additional feature of inputting the energy transmission factor f through the vapor shield region at the material surface as predicted by MAGFIRE. Special models also have been developed for non-ideal plasma effects and the calculation of ablated material enthalpy.

A set of measurements at different discharge energies was carried out to study ablation of the Lexan insulator breech in SIRENS (Fig. 10).

The geometric parameters for the breech region of SIRENS are:

Diameter = 4mm

Length = 12 cm

A typical pulse discharge current profile as a function of time; $I_{max} = 15$ kA at $t = 8$ μs, pulse length 100 μs; was used as the input to the code. The current profile of this reference shot was scaled to obtain the maximum current of different shots so as to compare the theoretical and experimental results at different plasma variables which include density, temperature, enthalpy and charge state. The heat flux to the insulator surface is determined from the plasma temperature by assuming that a fraction of the blackbody radiation, f, impinges on the wall. The variable, f, was varied from 0.2 to 0.01 and the total ablation depth from the code was compared to that from the experiment. Corroboration between the experiment and theoretical simulation of the electrothermal gun (SIRENS) was achieved for f ~ 0.2 at lower heat fluxes and f ~ 0.05 at higher heat fluxes; as shown in Fig. 11. This corresponds to the trends for f predicted by MAGFIRE.

The critical parameter involved in the ablation process is the fraction of blackbody radiation transmitted through the vapor shield, f. Fig. 11 shows that the ablation depth increases with an increase in the fraction of blackbody radiation through the vapor shield. In the case of the fraction of radiation transmitted through the vapor shield a higher flux of photons reaching the surface of an insulator, would produce a higher amount of ablation. Since the heat flux to the wall is proportional to the transmission factor, f, any increase in f implies a corresponding increase in ablation. The input joule heating energy is primarily distributed between radiation energy and internal energy of the plasma. Fig. 11 indicates that the variation in joule heating below about 2000 J yields a proportional change in radiation energy. However, above 2000 J the internal energy of the plasma plays a dominant role in the energy balance and the heat flux does not scale directly with input energy. A fixed value of the heat of sublimation, H_{sub}, for Lexan was adopted since the calculation of that parameter is based on similar principles as that for PTFE (Teflon).

Fig. 12 shows typical predictions of the average plasma density and temperature as a function of time, for two different values of f(f=0.1 and f=0.01).

Predictions from the code, ZEUS, indicates the following trend with respect to the fraction of radiation transmitted through the vapor shield to the wall surface. A higher value of f produces a larger amount of energy loss in the form of radiation. The incident radiation on the wall then produces ablation of the wall material. The cold particles from ablation entering into the plasma cools it down further. The higher radiation energy loss combined with the higher ablation rate gives rise to a lower temperature and higher density with $f=0.1$ relative to $f=0.01$.

The temperature of the bulk plasma rises rapidly as the current increases due to ohmic heating and reaches a peak at about the same time the current does. At this point of the discharge the electric power is large compared to the radiation power. The discharge does not dissipate the supplied power and heats up rapidly. The above mechanism may be considered to be adiabatic. The plasma density also starts to increase rapidly due to a rise in the temperature. However, due to an increase in the pressure within the channel, the particles are transported out in the axial direction. The plasma density reaches a peak value at about 10 μs later from the peak plasma temperature due to the competing effects of particle removel by axial transport and ablation. After about 50 μs the temperature reaches a quasi-stationary state, when the temperature of the discharge remains constant with time. This occurs due to the radiation power being of the same order of magnitude as the electric power. However, the rate of particle loss is still higher than the rate of ablation and so the density keeps decreasing.

Non-Ideal Plasma Effects

For the new regime of high density, low temperature plasmas encountered for our applications, several "non-ideal" effects were addressed; namely, a decrease in the effective ionization potential of the atoms in the vapor shield and the effect on transport coefficients such as resistivity, thermal conductivity, etc. The former phenomena will increase the ionization state of the vapor and will give rise to a stronger magnetic field induced current and shielding. The latter mechanism has been analyzed by several researchers[15,16]. We have included these formulations in ZEUS to find that predicted ablation depths are reduced by about 10% as shown in Figure 13. However, a more detailed analysis of the effect on equation-of-state and opacity data is currently being investigated.

CONCLUDING REMARKS

The project has been successful in predicting decreased erosion of surfaces exposed to high heat fluxes under railgun or EM launcher conditions. The significant reduction has come as a result of the proper modeling of the vapor shielding (VS) effect. Favorable comparison with experimental results supports our conclusion. A further decrease in surface erosion should come as a result of an applied magnetic field which should reduce turbulence in the VS boundary layer. Preliminary experimental measurements support this claim, but further theoretical work must be done which would include 2-D, and turbulent effects. Numerous researchers have reported reduction in heat transfer coefficients under somewhat different conditions (i.e. lower Reynolds numbers, no plasma effects, etc.). The key question that must be addressed in future work is the relative role of radiation transport (reported here) and turbulent convective transport in the overall energy transport through the VS boundary layer.

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14. J. G. Gilligan, D. Hahn, "The Magnetic Vapor Shielding Mechanism for Protection of Components Subjected to High Heat Flux", Proc. IEEE Int. Conf. on Plasma Science, Arlington, VA, June (1987), IEEE Cat. No. 87CH2451-3.

15. O. Auciello, O. Hankins, B. Wehring, M. Bourham, J. Gilligan, "Proof-of-Principle Experiment for the Magnetic Vapor Shield Mechanism", Final Report, DOD Equipment Grant DAAL03-86-G-0157, Nov. 1987.

16. Holliday, M. R., J. M. Doster, J. G. Gilligan, "Fusion Surface Material Melting, Ablation, and Ejection Under High Heat Loading", Fusion Technology 10, No. 3, Part 2A, 782-788 (1986).

17. M. R. Holliday, J. M. Doster, J. G. Gilligan, "Fusion Surface Material Melting, Ablation and Ejection Under High Heat Load," Trans. Am. Nuc. Soc. 51 (1986).

18. J. Gilligan, "Magnetic Vapor Shielding of Surfaces Under High Heat Load," Bull. Am. Phys. Soc. 30, No. 9, 1629 (1985).

19. J. Gilligan, "The Magnetic Vapor Shielding Mechanism for High Heat Load Protection," Final Report, ARO Contract, Sept. 1985.

Table I Summary of Parametric Studies for Vapor Shielding Effect

Source	Blackbody Temp., eV	2	3	5
	Heat Flux, W/m^2	1.6×10^{10}	8.3×10^{10}	6.4×10^{11}
	Pulse Length, μsec	10	10	10
	Energy Fluence, J/m^2	1.6×10^{5}	8.3×10^{5}	6.4×10^{6}
Iron	Energy reaching wall, J/m^2	3.8×10^{4}	9.0×10^{4}	2.6×10^{5}
	Transmission factor f, %	23.0	10.8	4.1
	Erosion Thickness, μm	0.7	1.5	4.5
Graphite	Energy reaching wall, J/m^2	7.8×10^{4}	1.7×10^{5}	4.5×10^{5}
	Transmission factor f, %	47.5	20.5	7.1
	Erosion Thickness, μm	1.1	2.4	6.4
Copper	Energy reaching wall, J/m^2	3.7×10^{4}	8.9×10^{4}	2.2×10^{5}
	Transmission factor f, %	22.7	10.7	3.5
	Erosion Thickness, μm	0.8	1.9	4.6

Table II Radiation Flux (W/cm^2) at Iron Wall Surface Subjected to 3 eV Blackbody Radiation after 10 μsec Pulse

Flux Limit	MAGFIRE	ANALYTIC	source[a]	vapor[b]
$(c/4)U_g$	1.5×10^6	3.4×10^6	1.8×10^6	1.6×10^6
$(c/2)U_g$	1.7×10^6	2.0×10^6	1.2×10^6	7.4×10^5
cU_g	1.8×10^6	1.1×10^6	6.6×10^5	4.7×10^5

a) Attenuated 3 eV Blackbody Radiation

b) Radiation from Vapor Shield Plasma

VAPOR SHIELD PROCESS

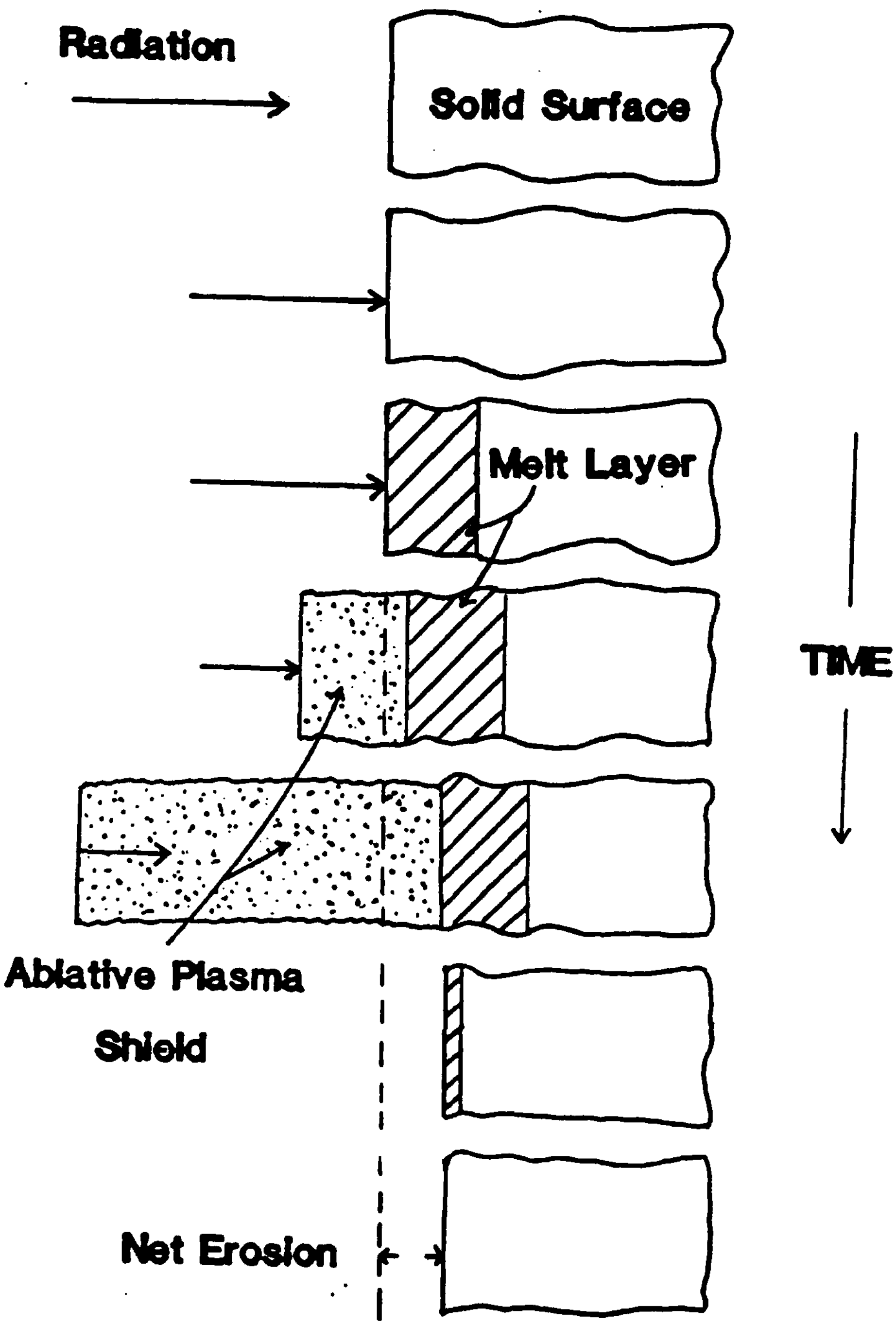
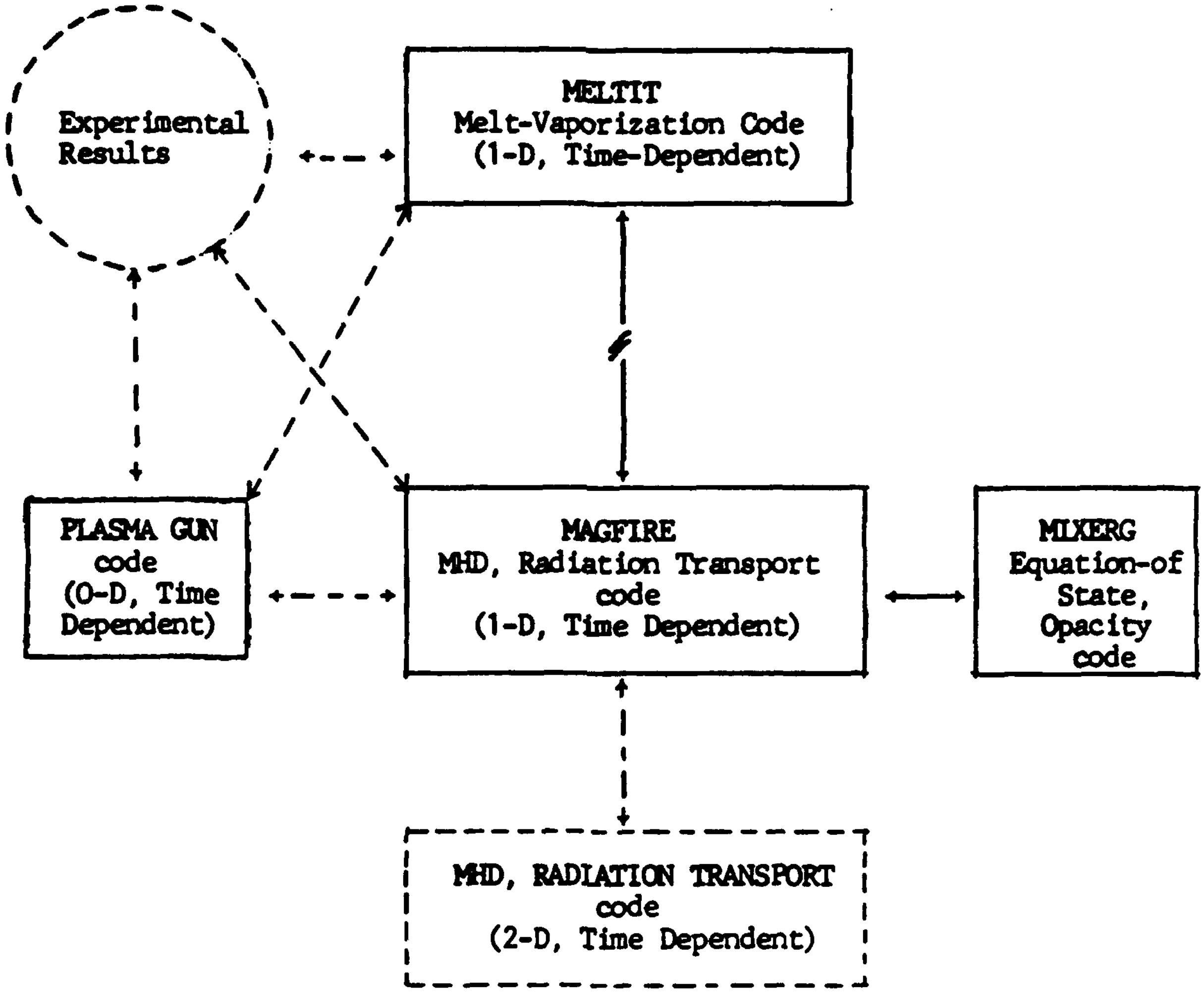


Fig. 1

Figure 2. Code Interrelationships



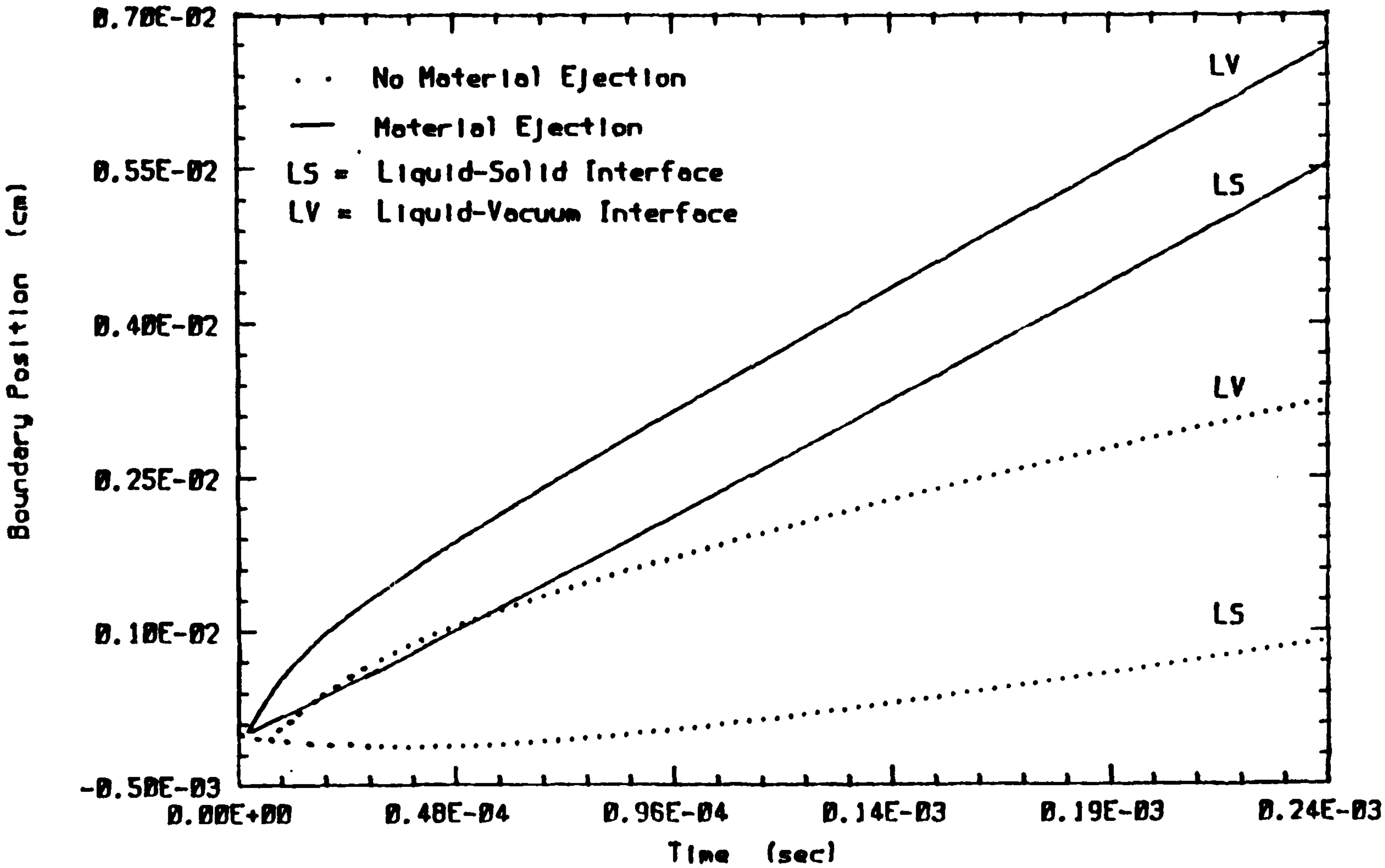


Figure 3
Time Varying Boundary Positions
Molten Material Ejection Comparison (ψ = 0 and 100)

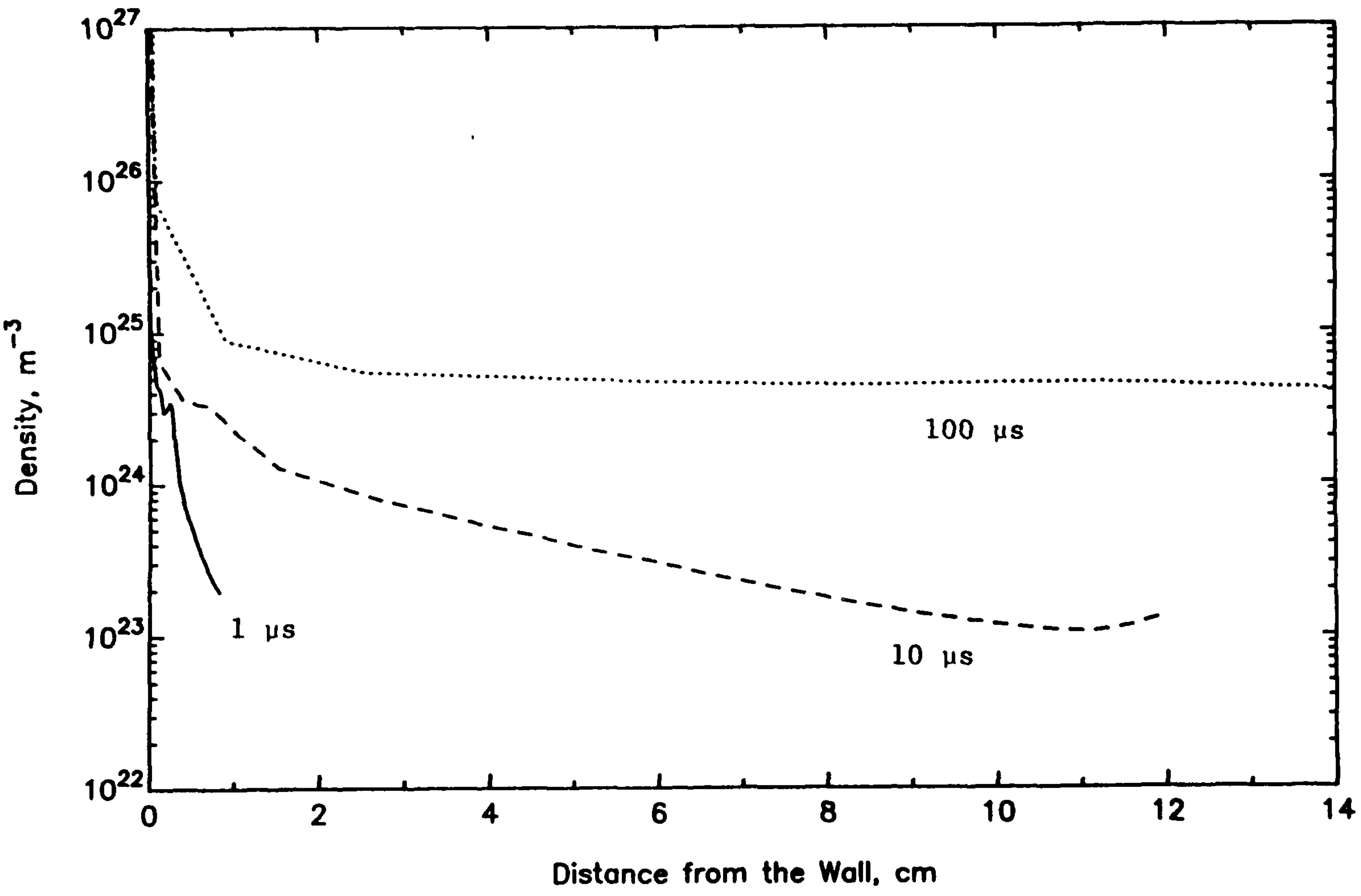


Fig. 4 Plasma Density Distribution for the case of an Iron Wall subjected to 3 eV Blackbody Radiation

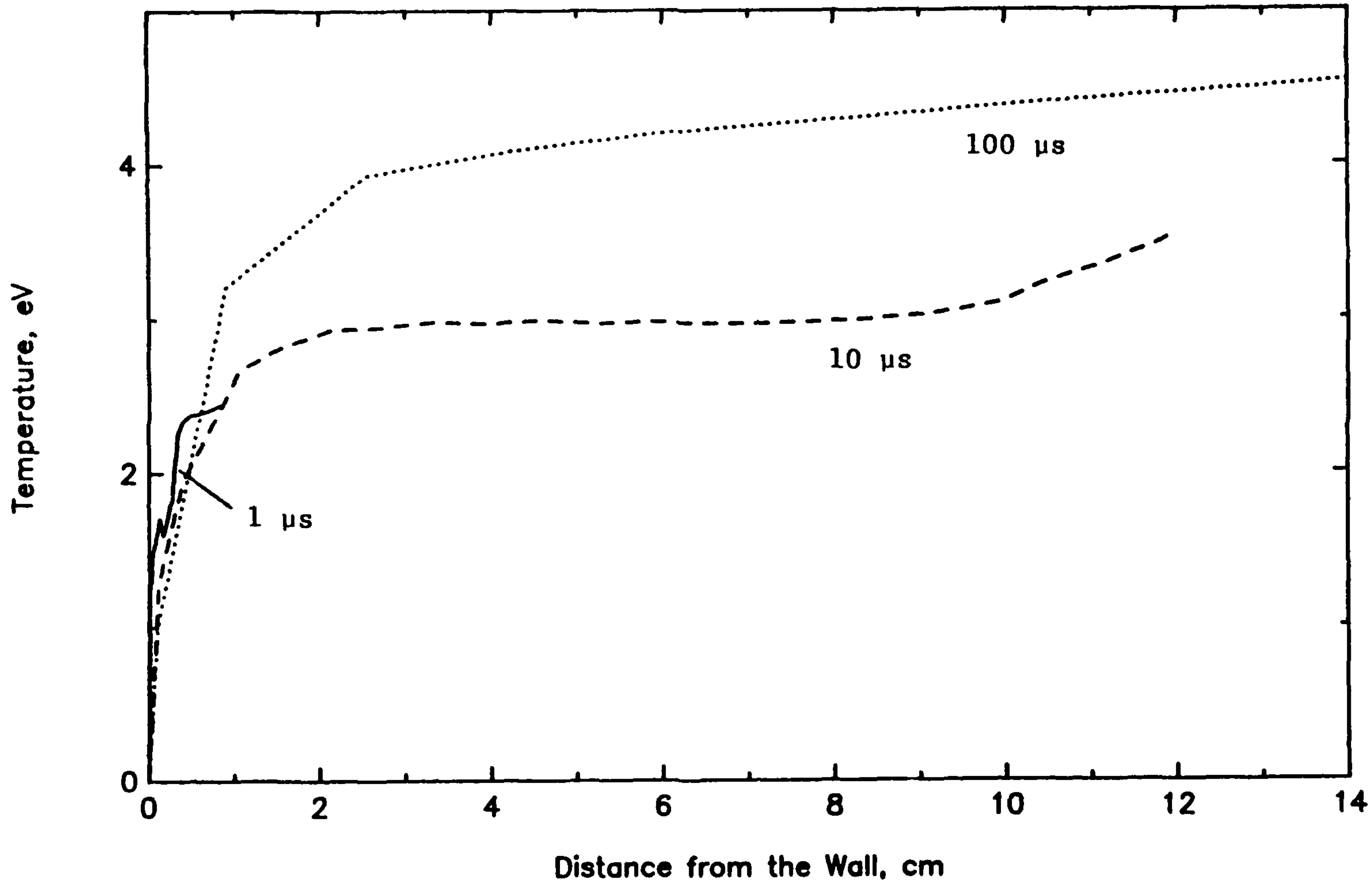


Fig. 5 Plasma Temperature Distribution for the case of an Iron Wall subjected to 3 eV Blackbody Radiation

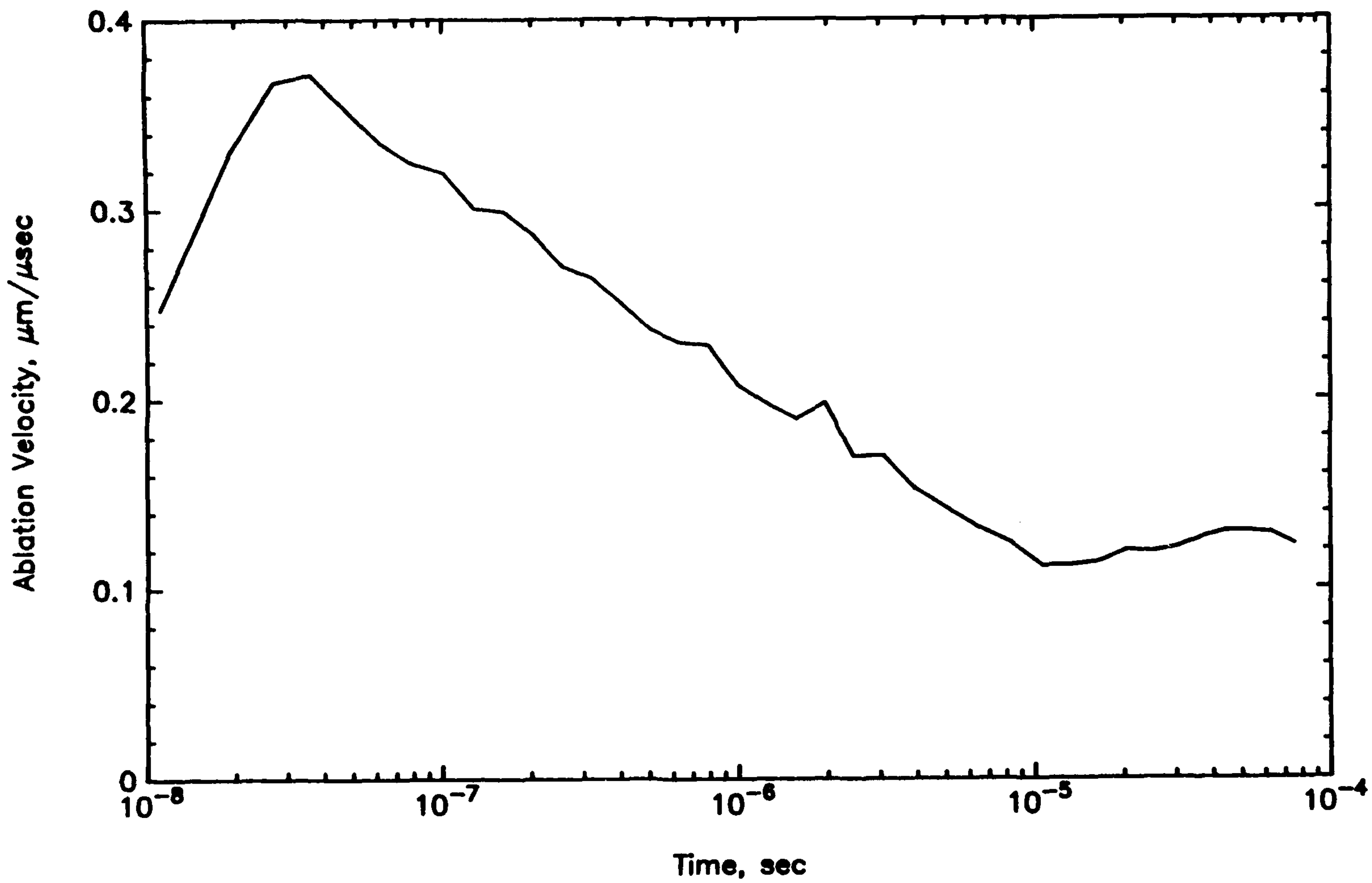


Fig. 6 Ablation Velocity of the Iron Wall subjected to 3 eV Blackbody Radiation

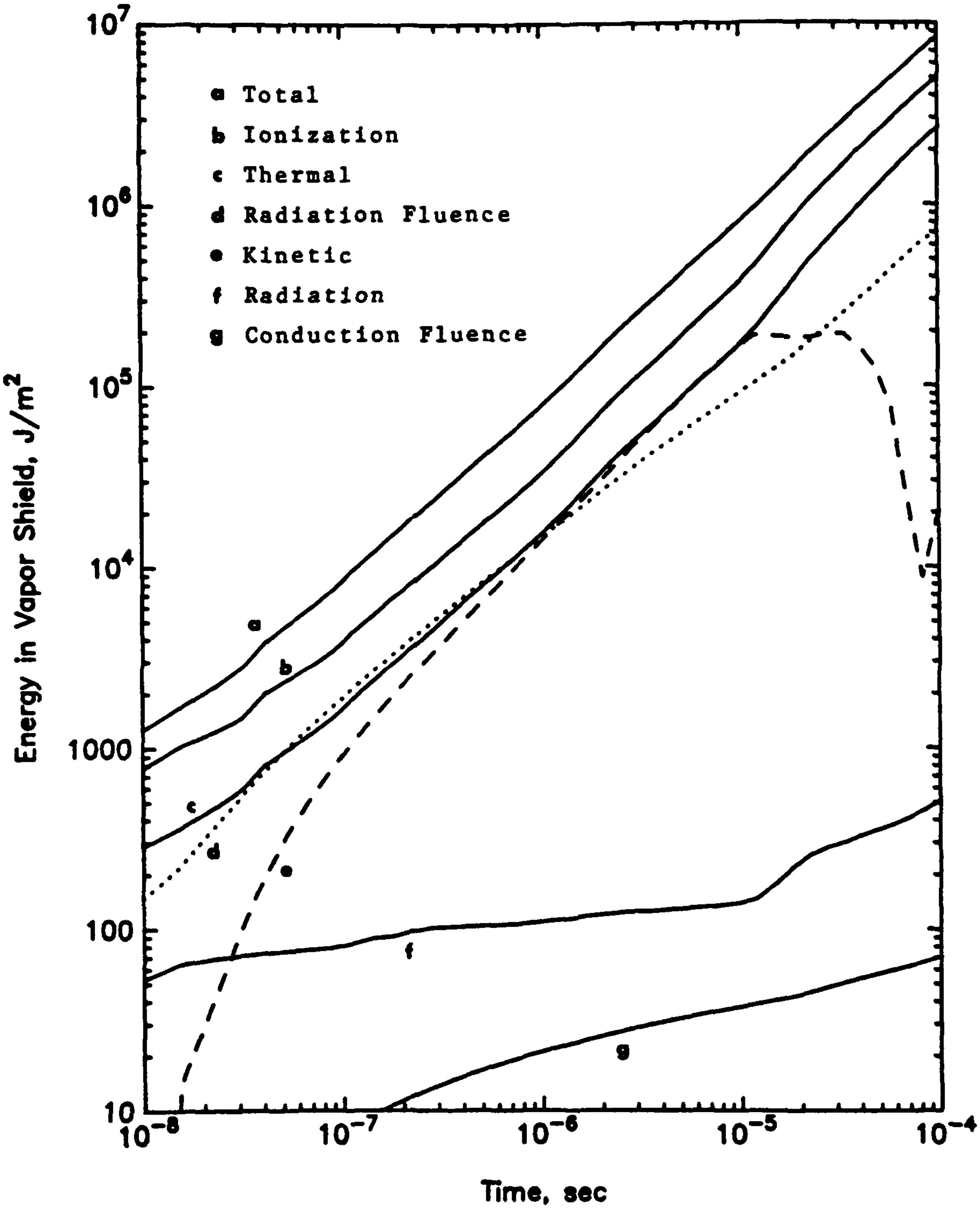


Fig. 7 Energy in Vapor Shield for an Iron Wall with 3 eV Blackbody Radiation

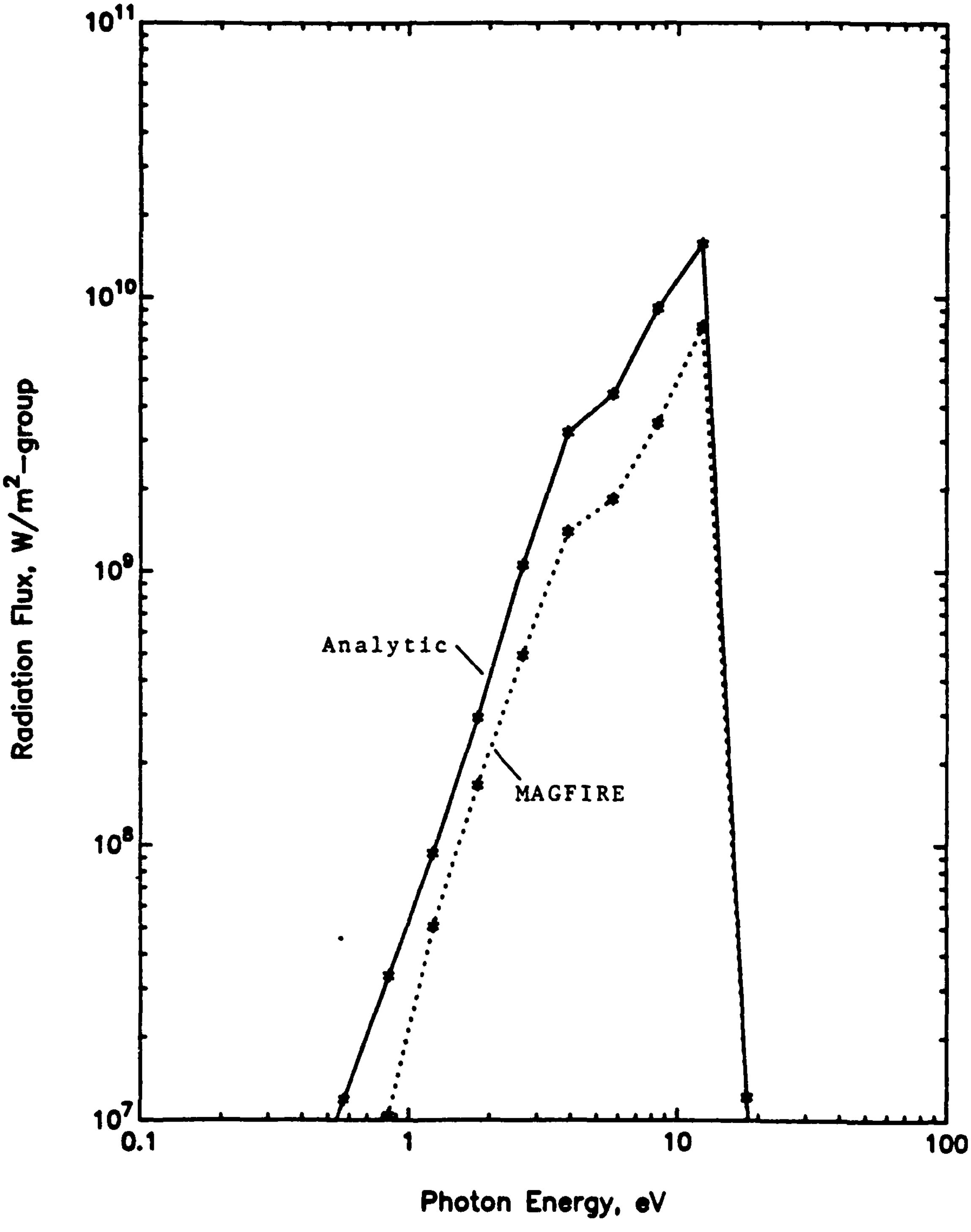


Fig. 8 Radiation Flux at Iron Wall Surface Subjected to a 3 eV Blackbody Radiation (10 μs, Flux Limit = (c/4) U_g)

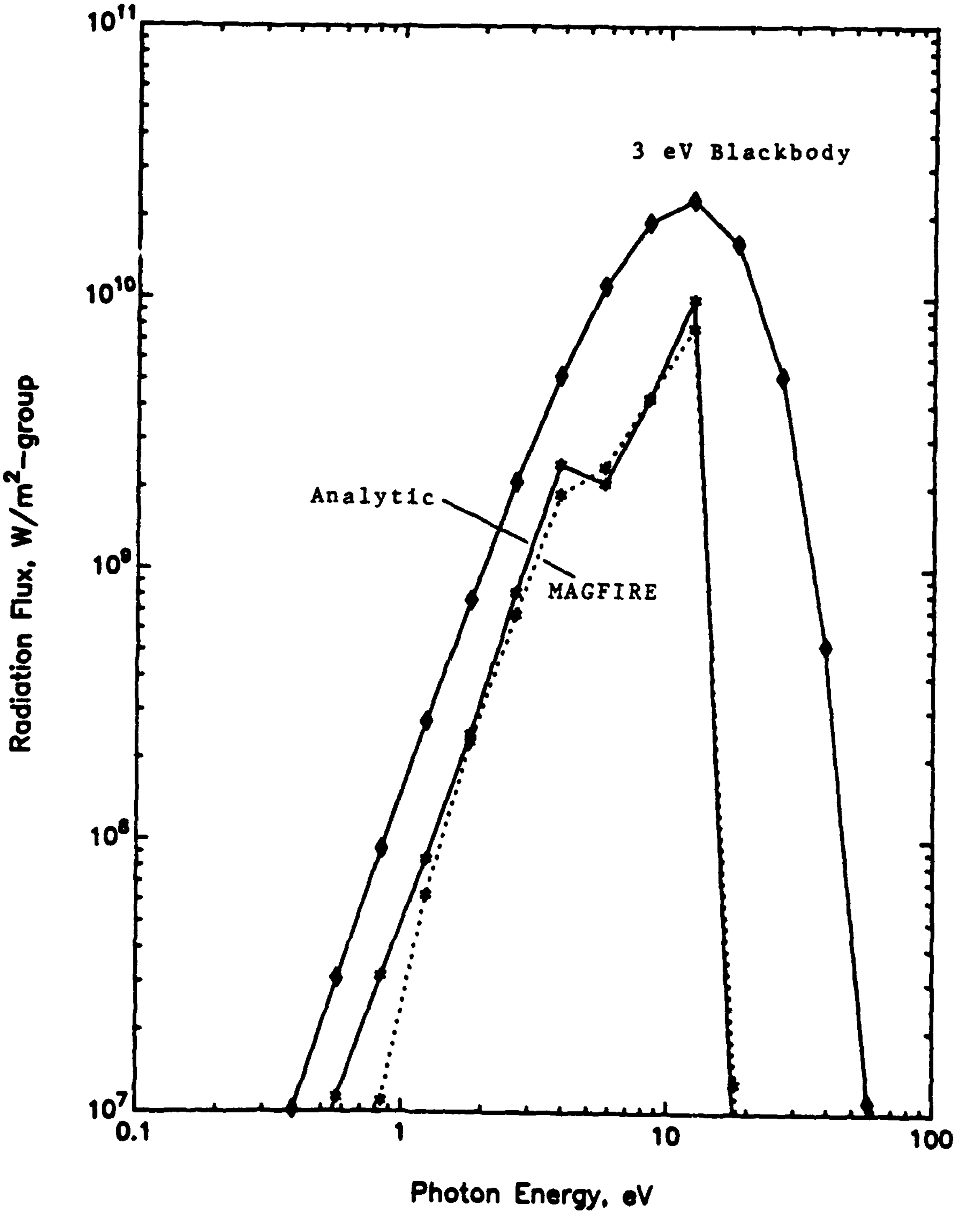


Fig. 9 Radiation Flux at Iron Wall Surface Subjected to a 3 eV Blackbody Radiation (10 μs, Flux Limit = (c/2) U_g)

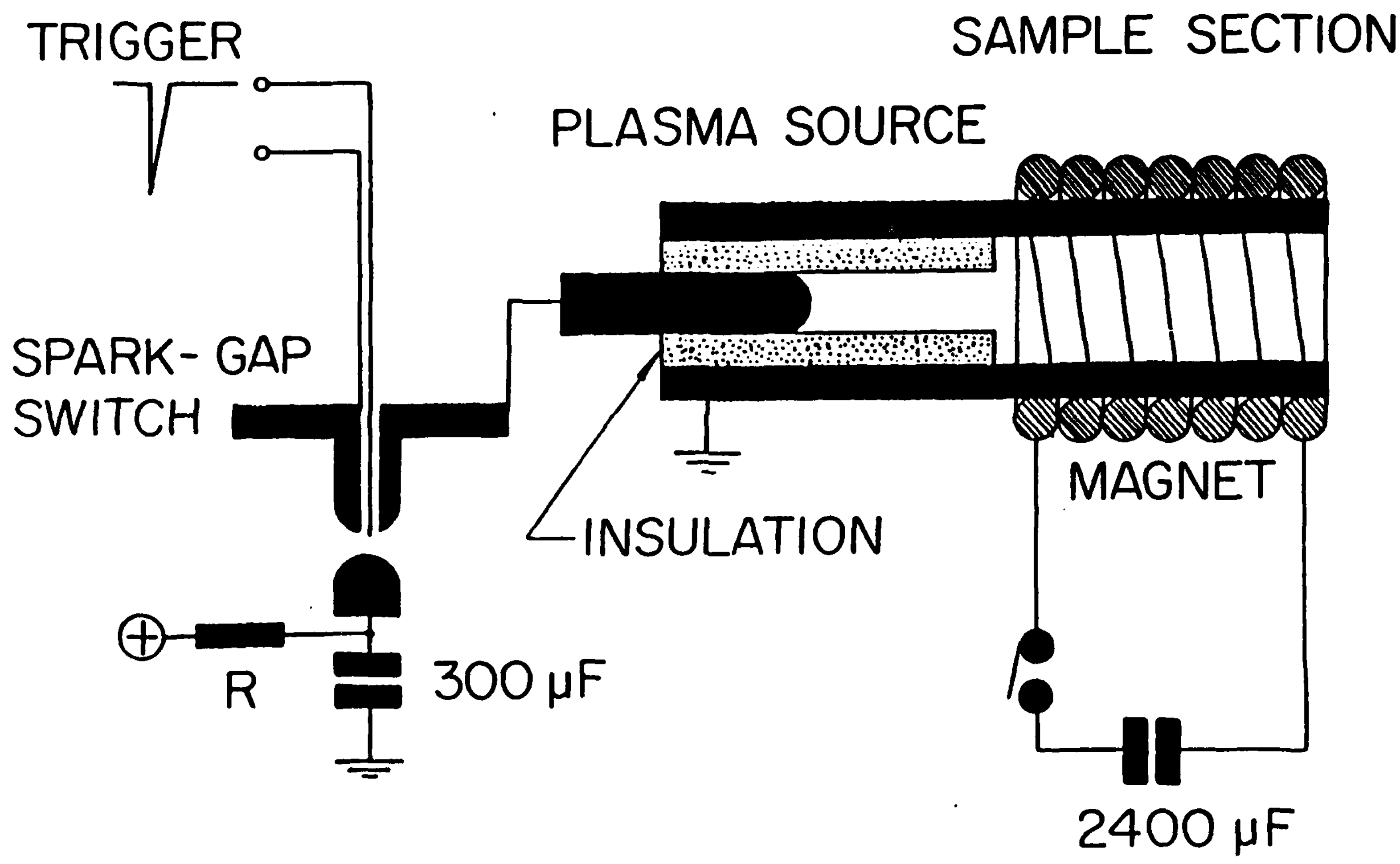


Fig. 10 Conceptual Design of the SIRENS Experiment

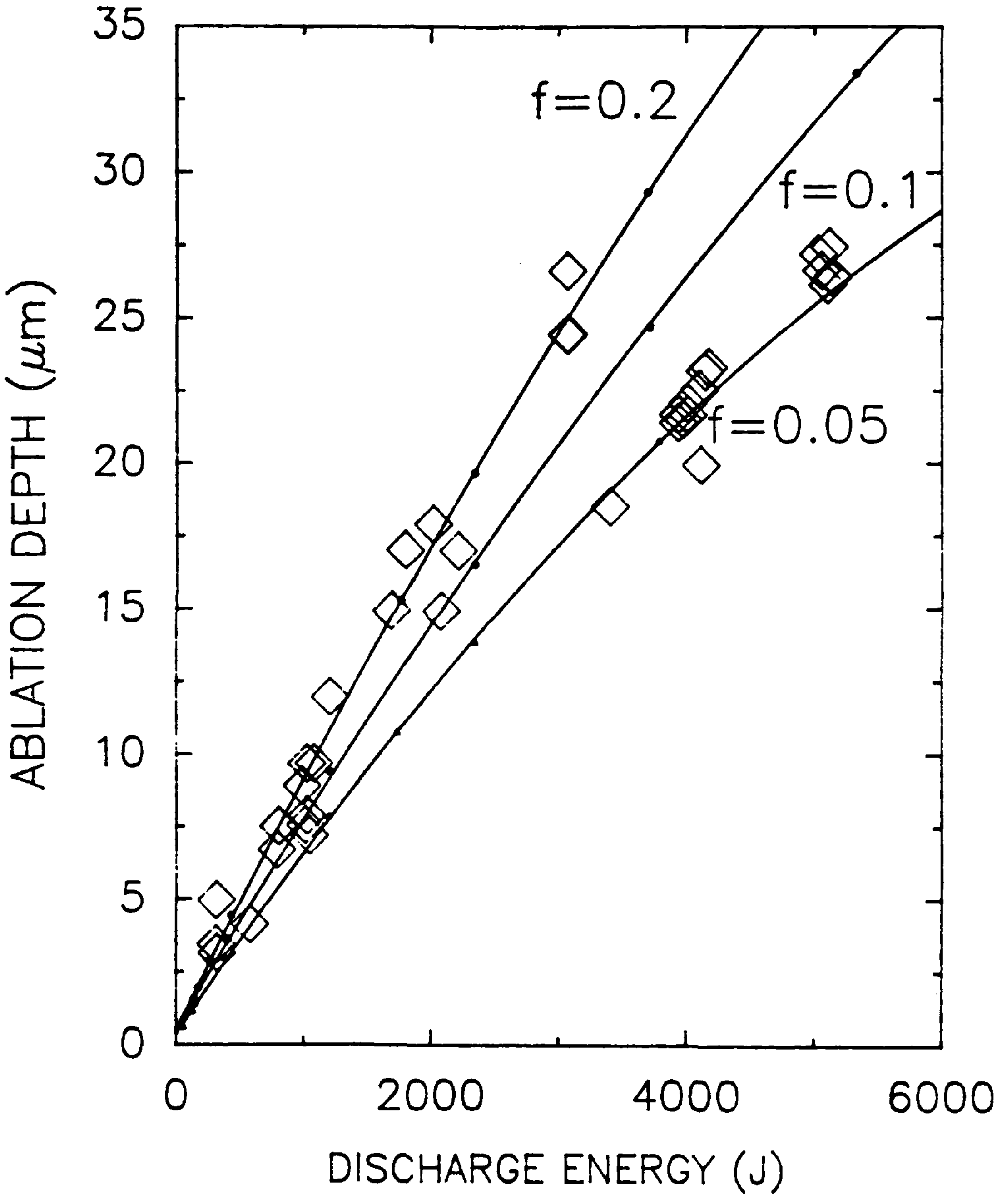


Fig. 11 Ablation Depth of Lexan Insulator in SIRENS. Symbols show the experimental data and solid lines are the result of ZEUS calculations.

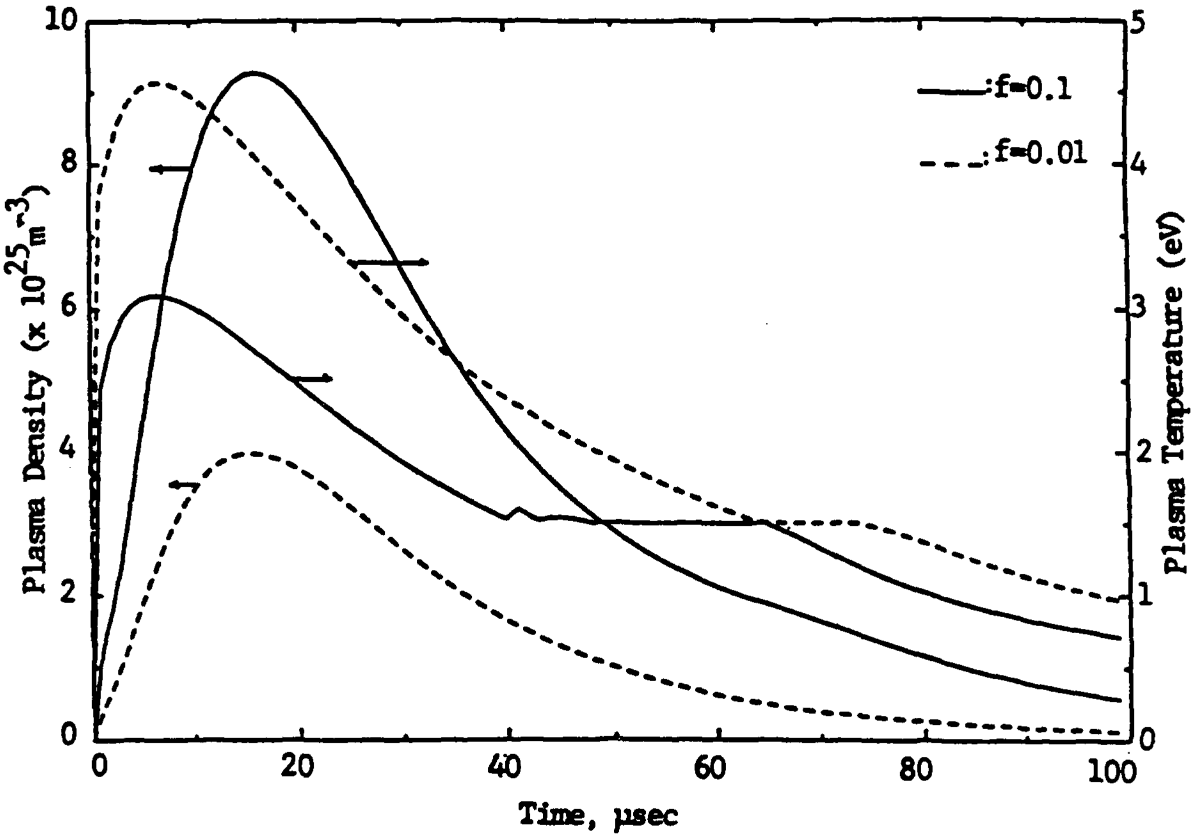


Fig. 12 Plasma density and temperature as a function of time for f=0.1 and f=0.01 as predicted by ZEUS for a Lexan insulator.

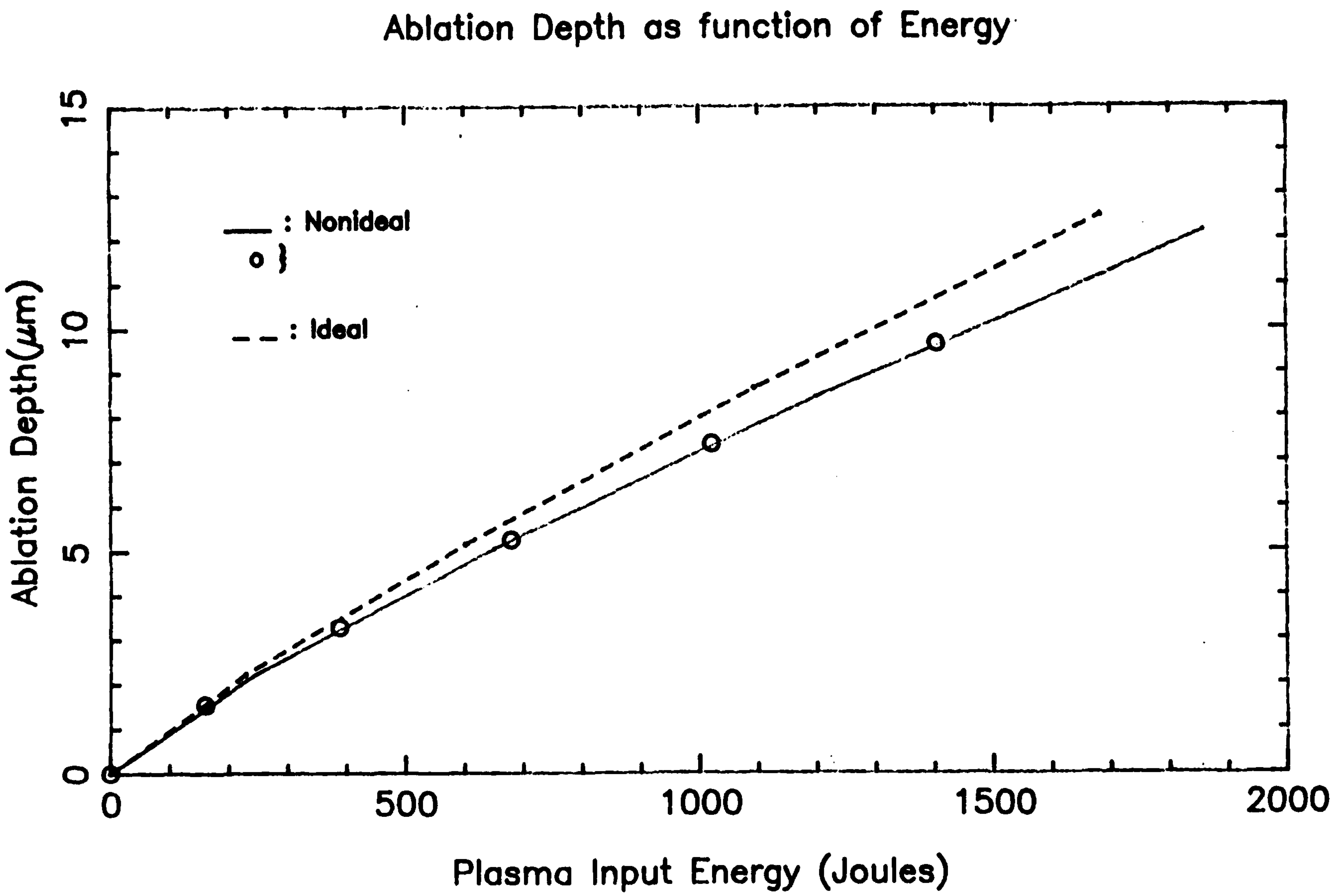


Fig. 13 Ablation Depth as Predicted by ZEUS for Lexan with f=0.05